ROOT DISTRIBUTION, ACTIVITY, AND DEVELOPMENT FOR BOREAL SPECIES ON RECLAIMED OIL SAND MINESOILS IN ALBERTA, CANADA

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ABSTRACT

Alberta's oil sands are located in the boreal forest where surface mining disturbs huge tracts of land. One such area, Syncrude Canada Ltd.'s Mildred Lake mine, contains waste overburden (OB) piles which can be saline and sodic (SSOB). The objectives of this research were to 1) determine SSOB material impacts on planted tree root distributions, 2) quantify root activity to identify plant species growing at depth, and 3) document coarse woody root structure for planted trees. Root distributions for three mixedwood stands on reclaimed OB in relation to electrical conductivity (EC) and sodium absorption ratio (SAR) were examined using soil cores. Root distributions followed a similar pattern with soil depth as those from undisturbed boreal forest stands and appeared unaffected by the SSOB at this stage; however, future monitoring will be required as the stands mature. Root activity was assessed for jack pine (jP) and white spruce (wS) stands on tailings sand (TS) and OB using a strontium (Sr) chloride tracer. Understory and tree foliage was collected prior to and after application to measure Sr concentration in the control, broadcast, and depth treatments. A small proportion of roots grew in the OB material regardless of its chemical properties. Results from the Sr tracer study suggested that these roots were probably from the clover, sow thistle, and grasses. Planted trees showed little to no change in Sr tissue content suggesting that there were little to no roots in the treatment zones, the understory species out-competed the trees for Sr accessibility, or the tracer was diluted in the tree biomass to undetectable levels. Root systems of planted jP trees older than 10 years and older than 20 years on TS and OB were excavated and the number and diameter of lateral roots, the degree of kinking and coiling, and the presence of a taproot were recorded. Excavated trees showed poor taproot development on 70% of the trees and numerous root deformities, suggesting that more emphasis is needed in correct planting techniques and good planting stock to ensure proper root development. Roots are critical components of boreal forest ecosystems; without healthy root systems productivity may decline, stands may be susceptible to windthrow, and general forest health may suffer.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ANOVA	Analysis of variance
ATB	Atmospheric topped bitumen
bb	Buffalo berry
bft	Bird's-foot trefoil
bP	Balsam poplar
cl	Clover
CT	Consolidated tailings
da	Dandelion
DP	Direct placement
DRU	Diluent recovery units
dw	Dogwood
EC	Electrical conductivity
fw	Fireweed
gb	Gooseberry
gr	Grasses
jP	Jack pine
kk	Kinnickinnick
MLSB	Mildred Lake settling basin
NRU	Naphtha recovery unit
OB	Overburden
PSV	Primary separation vessels
pv	Pea vine
rb	Raspberry
RGP	Root growth pressure
RLD	Root length density
RLD_u	Root length density for the upper 30 cm of soil
SAR	Sodium absorption ratio
sb	Strawberry
SCL	Syncrude Canada Ltd.
SD	Standard deviation
SPE	Saturated paste extract
SSOB	Saline-sodic overburden
sth	Sow thistle
SWSS	South west sand storage
tA	Trembling aspen
TOC	Total organic carbon
TOR	Tailings oil recovery
TS	Tailings sand
VDU	Vacuum distillation unit
wi	Willow
wS	White spruce

1 INTRODUCTION

Surface mining of the oil sands near Fort McMurray, Alberta [by Syncrude Canada Limited (SCL)] moves more than 120,000 m^3 of mineral soil, peat, and overburden each day (Meier and Barbour, 2003). Prior to mining the oil sands, the land is drained if necessary, the trees are harvested, and the muskeg or peat and surface mineral soil are scraped off and saved for reclamation purposes. Below this surface of mineral soil and above the oil sands is the overburden (OB) material, and in the Fort McMurray area, this layer often consists of saline-sodic clay shale from the Clearwater geologic formation and is termed the saline-sodic overburden (SSOB). The SSOB is removed and then used to fill in the mined out pits afterwards, constructing new upland landscapes which are then capped with a mixture of secondary surface mineral soil and peat from the recently salvaged, stockpiled material. The oil sands are mined, the bitumen extracted and upgraded, and the byproducts further processed and managed. Tailings sand, one byproduct of the extraction process, is typically allowed to settle and drain in tailings sand settling basins which are then reclaimed in much the same manner as the SSOB areas, and also are capped with mineral soil and peat. All reconstructed landscapes are planted with boreal tree species native to the region, primarily white spruce [wS; *Picea glauca* (Moench) Voss], trembling aspen (tA; *Populus tremuloides* Michx.), and jack pine (jP; *Pinus banksiana* Lamb.).

Once the decommissioned oil sand mine sites are reclaimed, SCL can apply for certification which will ultimately release them from their responsibility to the disturbed land and indicates that reclamation standards have been met or exceeded for that site (Alberta Environment, 1999). However, under the Conservation and Reclamation Regulation, "the industry is liable for the first 25 years for surface reclamation issues involving topography, vegetation, soil texture, or drainage. Liability reverts to the Alberta government after this 25 year period" (Alberta Environment, 2008). If a forest is intended for commercial growth and harvesting, it must meet certain requirements for acceptable tree species of adequate volume and quality (OSVRC, 1998). Only native tree species are planted back into the region as per the current reclamation guidelines. If tree root growth is hampered, the volume and quantity of commercial lumber available may not be sufficient for future harvesting. By examining the root systems of the trees, an indication of the forest's health or future health can be obtained. Root density distributions, depth of rooting, and root system morphology are three of the many options available to determine this. Not all forested areas will be intended for future commercial harvesting; however, all the reclaimed sites must have a sustainable, functioning ecosystem above and below ground.

Since 1978, over 4700 ha (22% of the disturbed land area) have been reclaimed at the SCL mine site in a manner similar to that described above and planted with more than 5 million trees (SCL, 2008). The reconstructed landscapes are intended to mimic the natural soil qualities of boreal ecosystems and are required to restore forest productivity to, at a minimum, its pre-disturbance level (OSVRC, 1998; Alberta Environment, 1999). The capping or cover soil (peat and surface mineral soil or mixture of both) is intended to provide a suitable medium for tree rooting and growth, whether in terms of water storage, nutrient supply, or rooting depth. The SSOB which was once several meters to tens of meters below the soil surface is now typically within 1 m of the surface, placing it in closer proximity to the rooting zone of boreal species, many of which are not salt tolerant (Howat, 2000). Given the saline and sodic nature of the overburden material and some upward migration of salts into the soil capping above the interface of the SSOB (Kessler, 2007), there could be increasing chemical barriers for root growth of boreal trees, adversely affecting the continuing root development as the forest ages.

The intent of this research was to determine if rooting of planted trees was impacted by the salinity and sodicity of the OB material with the hypothesis that root growth and development were not impacted by the reclamation material and its properties. The following research objectives were outlined:

1. to measure the distribution of roots in different aged trembling aspen (*Populus tremuloides* Michx.) and white spruce [*Picea glauca* (Moench) Voss] mixed-wood stands on reclaimed saline-sodic overburden sites;
2. to determine if root length density is related to electrical conductivity (EC), sodium absorption ratio (SAR), bulk density, or pH;

3. to quantify root activity using a strontium chloride tracer in different reclamation prescriptions (i.e., saline-sodic overburden and tailings sands); and
4. to document root development of planted jack pine (*Pinus banksiana* Lamb.) plantations on different reclamation prescriptions.

This thesis is comprised of six chapters. This first chapter gives a broad background about the oil sands region and outlines the objectives of the research. Chapter 2 is a literature review which identifies the processes from mining to reclamation in order to understand the excavated materials, byproducts, and altered ecosystem the study encompassed. It also presents background information on typical native boreal species used in reclamation in regards to rooting habits and influence of environmental factors typical of surface mined sites, defines root activity and briefly presents one method for measurement, and discusses some of the issues that have been identified in outplanting jack pine seedlings.

Chapters 3 to 5 present the three different research studies undertaken to address the objectives. Root distributions for mixedwood stands on reclaimed saline-sodic overburden in relation to EC and SAR profiles are examined in Chapter 3. Chapter 4 assesses root activity on both tailings sand and overburden sites using a strontium tracer. In Chapter 5, the root development of jack pine trees of two different ages and on two different sites are examined for lateral roots, taproots, and possible root deformities. Finally, Chapter 6 presents an overview and general discussion of work reported on in Chapters 3 to 5, with emphasis on how the findings relate to general reclamation success and ecosystem sustainability.

2 LITERATURE REVIEW

2.1 Surface Mining and Reclamation Practices at Syncrude Canada Limited

The majority of Alberta's oil sands (bitumen saturated sands) are found in the Athabasca, Wabasca, Peace River, and Cold Lake deposits. Most of the deposits are not shallow enough to economically access them by surface mining. As such, the mineable area is limited to the northern Athabasca deposit where the overburden is less than 50 m thick (Mossop et al., 1982). Besides being the largest oil sand deposit in Alberta, the Athabasca is also the only deposit with surface outcrops. The mines are located in the most lucrative location, near the Athabasca River where the oil sands are closest to the surface (OSERN, 2003). With advances in technology, the current capabilities allow open pit mining to less than 250 m of overburden (Bauman et al., 2000).

The Athabasca deposit is located in the boreal forest region of Alberta. Stands of trembling aspen (*Populus tremuloides* Michx.), balsam poplar (*Populus balsamifera* L.), white spruce [*Picea glauca* (Moench) Voss], black spruce [*Picea mariana* (P. Mill.) B.S.P.], and jack pine (*Pinus banksiana* Lamb.) are common in the area. Other tree species found are balsam fir [*Abies balsamea* (L.) P. Mill.], tamarack [*Larix laricina* (Du Roi) K. Koch], and paper birch (*Betula papyrifera* Marsh.) (OSERN, 2003).

To gain access to the oil sands, all of the trees in an area are harvested, followed by removal of the overburden. Overburden (OB) is typically considered as the surface material that overlies the mineable oil sands – the muskeg (peat), topsoil, sand clay, and gravel. The topsoil and peat are salvaged and either used directly for reclamation or stockpiled for future reclamation activities. Overburden is generally non-homogeneous, non-saline, and slightly alkaline (OSERN, 2003). However, much of the OB which occurs at the Syncrude mine site can be saline and sodic in nature due to the marine clay-shales which make up much of the geological formation present in this area. This saline-sodic material in particular is referred to as the saline-sodic overburden (SSOB) in the remainder of this document. Also, for the purposes of this document, the term overburden (OB) is used to refer only to the material that is not salvaged for reclamation.

2.1.1 Surface Mining of the Oil Sands

2.1.1.1 Geology

The oil sand reserves are primarily found within the Lower Cretaceous Mannville Group and its equivalents, although, some of the overlying Clearwater Formation sands (Wabiskaw Member) are partially oil saturated (Mossop et al., 1982; Rogers, 2003). The Clearwater Formation is an electrically conductive marine sedimentary deposit of fine to medium sand, silt, clay and shales (Bauman et al., 2000). Below this is the Cretaceous McMurray formation (up to 150 m thick) which holds the majority of the oils sands (Figure 2.1) and is bound below by conductive Devonian limestone and marls (Bauman et al., 2000). The McMurray Formation is divided into the upper, middle, and lower units, but these subdivisions have not been formalized (Gingras and Rokosh, 2004; Mathison, 2003). Generally, the McMurray Formation is fluvial in the lower parts, estuarine in the middle, and marine shoreface in the upper unit (Gingras and Rokosh, 2004). In total, it averages 40 to 60 m of uncemented quartz sand, complexly interbedded with subordinate associated shales and rare ironstone beds (Mossop et al., 1982).

2.1.1.2 Mining

After the trees are harvested, the various organic and mineral layers of the soil profile are stripped. The muskeg or peat material and suitable mineral soil (often referred to as secondary material) are either direct placed at a reclamation site or stockpiled for later use. Below this and directly overlying the oil sands is a layer of clayey and rocky material (OB) often composed of Clearwater shale (Bauman et al., 2000), as mentioned previously. This OB material is removed and used as the construction material to fill the mined out pit and is eventually reclaimed using the salvaged peat and mineral soil. The oil sands are mined, either by draglines and bucketwheel reclaimers which place the oil sands onto a conveyor directly feeding the extraction plant (being phased out); or by truck and shovel operations which are used to mine and transport the oil sands to the crusher plant (SCL, 2004). At the crushers, a slurry of oil sands and hot water is created and pumped to the extraction plant (hydrotransport) (SCL, 2004).

Mannville Group	Grand Rapids Formation				
	Clearwater Formation				- marine clay shales - high electrical conductivity
	Wabiskaw Member			(Gingras and Rokosh, 2004)	(Bauman et al., 2000)
	McMurray Formation	Upper	Red	- highly variable - generally open marine deposits - shallow, low-energy shoreface deposits and small deltaic complexes	- coarser deposits are typically the richest oil sands, but vertical distribution of bitumen is complex - may be bitumen in clean sand interbeds - thick water sands may occur within bitumen
			Green		
			Blue		
		Middle		- inclined heterolithic stratification - deposition on tidally influenced point bars - bracking-water trace fossil assemblage - fossil estuary	
		Lower		- medium to coarse grained - massive appearing to crudely cross-bedded - fluvial natured beds	- thick, massive fluvial sands - usually barren in oil - pore water from fresh to brine

Figure 2.1. Mannville Group Formations in the Athabasca oil sands and their qualities. [Sources: Adapted from literature and figures presented by Mossop et al., 1982; Gingras and Rokosh, 2004; Mathison, 2003; and Bauman et al., 2000.]

2.1.1.3 Extraction

Because the Athabasca oil sands are water wet (i.e., have a thin, 0.1 μm film of water surrounding each grain), the sand and bitumen can be separated using hot water extraction (OSERN, 2003). Material that is transported by the conveyors proceeds through tumblers and is converted to slurry by steam, hot water and caustic soda (NaOH) while being rotated for aeration (SCL, 2004). This slurry is blended with that from the hydrotransport system. It passes through several different types of primary separation vessels (PSV) allowing the bitumen to float to the top. The sand settles out and the middlings are pumped to tailings oil recovery (TOR) vessels which recover most of the remaining bitumen. Froth from the TOR vessels is recycled to the PSVs while middlings continue to a secondary floatation plant and TOR vessels. Froth from the secondary flotation plant in combination with the primary froth are deaerated and heated and then fed to the froth treatment plant (SCL, 2004). The froth is diluted with naphtha and processed to remove water and tailings that might otherwise reach the upgrader (SCL, 2004). Naphtha is removed at the naphtha recovery unit (NRU). The tailings that remain consist of coarse sands; a liquid component of water, fine silt, and clay particles; and some residual hydrocarbons. These materials are stored in specifically designed structures (tailings sand settling basins) that allow solids to settle out and provide water for reuse in processing. Tailings sand (TS) tends to be slightly alkaline from the added sodium hydroxide in the extraction process. Mildred Lake Settling Basin (MLSB) and Southwest Sand Storage area (SWSS) are TS settling basins. The remaining water and fines from SWSS move via gravity to Base Mine Lake for further settling (SCL, 2004).

2.1.1.4 Upgrading

Upgrading refers to the process by which bitumen is converted to a high quality, light sweet crude oil (Syncrude Sweet Blend) with low sulfur (S) content (SCL, 2004). In the diluent recovery units (DRU), the naphtha and light gas oil are distilled off while hot atmospheric topped bitumen (ATB) is produced to feed the fluid cokers, LC-Finer hydroprocessor, and vacuum distillation unit (VDU) (SCL, 2004). After distillation of heavy and light gas oils in the VDU and breakdown of bitumen through hydrogen reactions in the LC-Finer hydroprocessor, the fluid cokers crack or breakdown the residuum into lighter products under high temperatures (SCL, 2004). Naphtha and gas oils are sent to hydrotreaters where S and nitrogen (N) are removed. In this process, hydrogen sulfide (H_2S) and ammonia (NH_3) are produced. The H_2S is converted to elemental S and stored in blocks, while the NH_3 is burned in the CO boilers. Sour fuel gas is sent to amine treaters for H_2S removal resulting in sweet fuel gas which is used as an energy source (SCL, 2004). Coke is burned in the reactors; however, excesses are mixed with water and transported to coke cells in the mine area to be stored for potential future use via reclamation capping.

By means of the mining, extraction, and upgrading processes, several materials and byproducts remain. These are stored within or used in the development of new landscapes which need to be reclaimed. The OB material, which tends to be highly saline and sodic in the area being mined by SCL; the resultant TS from extraction; fine tails; consolidated tailings (CT); coke; and elemental S are each unique in their composition and therefore, in their requirements for reclamation. Thus far, the dominant materials which have been reclaimed are TS and OB (materials for which procedural guidelines have been established). Reclamation procedures for the other byproducts are being investigated by mining companies and numerous researchers.

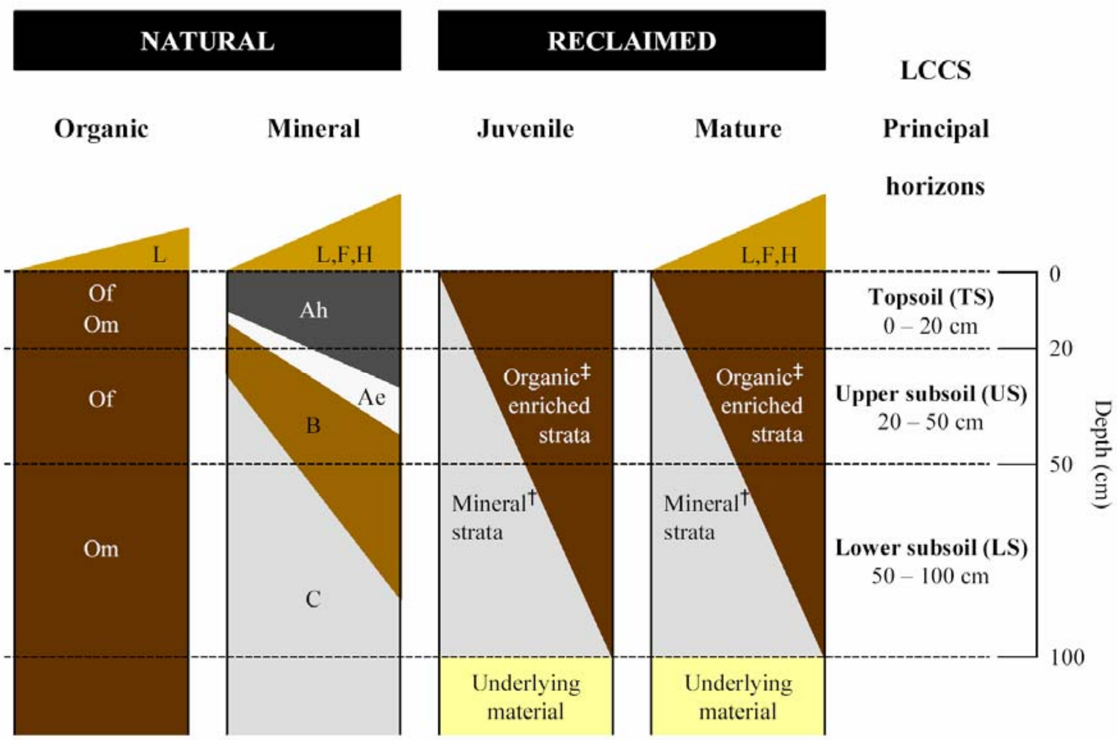
2.1.2 Reclamation Process

Due to the nature of open pit mines, huge tracts of land are disturbed and thousands of tonnes of soil are moved every day. Reclamation mandates require the resultant landscape at SCL be suitable for a future productive forest; that it will be stable, non-hazardous, have favorable soil conditions, and a capability equivalent to that which existed prior to disturbance (OSERN, 2003). Over the years, regulations and guidelines for reclamation in Alberta have changed. These adjustments, in addition to data gathered from continuous monitoring, have necessitated Syncrude Canada Ltd. to modify the reclamation program over time (OSVRC, 1998). Due to the adaptive or responsive nature of reclamation practices, various areas have undergone separate procedures that were acceptable at different time periods.

The placement of suitable cover material is typically done in the winter with spreading of the reclamation material finished in the early spring. Barley or oats are often seeded on reclaimed slopes to add vegetation cover and prevent erosion (OSVRC, 1998). Woody plants or trees are selected based on typical ecosites of the boreal region which are most similar to the field conditions of the reclamation profile. The substrate material, landscape features, and the moisture regime are all considered in the selection for the desired species composition. The seed source or tree variety must be registered with the Alberta Tree Improvement and Seed Center and be native to the area (OSVRC, 1998). Trees are planted to densities of 1800 to 2200 stems per hectare.

Typical forest soils have profiles that include the LFH, A, B, and C horizons, or O (B, C) horizons in organic soils (Figure 2.2). A typical reclaimed profile is described by three "horizon" designations or layer descriptions. The topsoil (TS) layer is the 0 to 20 cm depth which does not include the surface organic litter or peat unless it is mixed with at least 17% mineral soil (dry weight basis) (Leskiw, 1998). The next layer is upper subsoil (US) from 20 to 50 cm, and finally the lower subsoil (LS) which is considered to be the 50 to 100 cm depth. A 1 m thick profile is evaluated for soil capability ratings used in the land capability classification (Leskiw, 1998; OSVRC, 1998). This system is used to rate the future forest productivity on the reclaimed areas.

Soil replacement occurs via two options, either a 'one-lift' or 'two-lift' technique. In the one-lift method, 25 to 50 % (by volume) of mineral soil is stripped off with the peat and incorporated (OSRRN, 2004; OSVRC, 1998). This is referred to as the peat-mineral amendment/mix or the cover soil mix and is generally spread to a depth of 15 to 50 cm over the prepared site (OSRRN, 2004; OSVRC, 1998). For overburden, the amendment is typically peat with coarse-textured material (sand and gravel), while the amendment for tailings sand incorporates fine-textured till, clay, or silt into the peat (OSVRC, 1998). For the two-lift approach, a 50 cm cap of sandy or clayey subsoil is placed over the substrate and then followed up with a 15 to 25 cm cover soil mix. These basic designs are adapted depending on the quality of the mineral component of the mixture which determines the drainage and nutrient retention properties (OSVRC, 1998). Placement prescriptions are also modified if no peat-soil amendment is available for use or if the substrate happens to be SSOB from the Clearwater or McMurray Formations. In the former case, 50 to 70 cm of sandy or clayey material slightly enriched with organic matter (OSVRC, 1998) may be used instead of the cover soil mix, while the latter case requires a total cover or capping depth of 1 m (Figure 2.3 and 2.4). The capping material



† Mineral horizons are defined as those having less than 17% total organic carbon (TOC)

‡ Organic-enriched strata are mineral horizons containing organic matter (i.e., peat/mineral mixes and shallow soil salvage). In the cases where the surface strata of a reclaimed soil or natural mineral soil with an O layer contain 17% or more TOC it is not considered to contribute to the moisture regime of the soil.

§ These profiles are generalizations. Each soil type presented is characterized by wide ranges of variability in horizon thickness and development.

Figure 2.2. Schematic diagram of the principal horizons applied to idealized§ natural and reclaimed soil profiles. [Source: CEMA, 2006.]

OVERBURDEN

	One-Lift								Two-Lift					
	Peat Mineral Mix				Organic Enriched Mineral Material				Peat Mineral Mix Over Sandy Loam or Finer Subsoil					
Class†	2	4	2	3	2	3	4	5	2	3	2	3	4	5
Description	100 cm peat mineral mix over OB	100 cm peat mineral mix over OB	> 50 cm of peat mineral mix over OB (depths reduced if no salinity/ sodicity)	20 to 50 cm of peat mineral mix over OB (depths reduced if no salinity/ sodicity)	> 50 cm of loamy or clayey DP material enriched with organic carbon over OB	> 30 cm of loamy or clayey DP material enriched with low organic carbon over OB	100 cm mineral soil slightly enriched with organic matter over OB	100 cm mineral soil slightly enriched with organic matter over OB	> 20 cm of peat mineral mix over >30 cm loamy or clayey subsoil over OB	> 20 cm of peat mineral mix or >30 cm of compacted loamy or clayey subsoil over OB	> 20 cm of peat mineral mix over >30 cm of sandy loam subsoil over OB	< 20 cm of peat mineral mix over >30 cm of sandy loam or loamy sand subsoil over OB	20 cm peat mineral mix over 80 cm mineral soil over OB	20 cm peat mineral mix over 80 cm mineral soil over OB
Moisture Regime	mesic	subhydric	subhygric	mesic	subhygric	mesic	hygric	subhydric	subhygric	mesic	mesic	submesic	hygric	subhydric
Target Ecosite‡	d,e	g,h,i,j,k	d,e,f	d	g	c	g,h	l,j,k	d,e,f	d	c,d,e	b	g,h	l,j,k

† Soil Capability Class, rated from 1 (land having no significant limitations) to 5 (land having severe limitations) in terms of successful forest production

‡ Target Ecosites, as outlined (with moisture regime/nutrient regime) by OSVRC (1998) and GDC (2005) from Beckingham and Archibald (1996).

b = blueberry (submesic/medium)
c = Labrador tea-mesic (mesic/poor)
d = low-bush cranberry (mesic/medium)
e = dogwood (subhygric/rich)
f = horsetail (hygric/rich)
g = Labrador tea-subhygric (subhygric/poor)
h = Labrador tea/horsetail (hygric/medium)
i = bog (subhydric/very poor)
j = poor fen (subhydric medium
k = rich fen (subhydric/rich)
l = marsh (hydric/rich)

Figure 2.3. Soil handling options and related soil capability classification for overburden reclamation. [Sources: adapted from OSERN (2003) and OSVRC (1998).]

TAILINGS SAND

	One-Lift									Two-Lift					
	Peat Mineral Mix				Organic Enriched Mineral Material					Peat Mineral Mix Over Sandy Loam or Finer Subsoil					
Class†	2	4	2	3	2	3	3	4	5	1	2	2	3	4	5
Description	> 50 cm of peat mineral mix over TS	50-100 cm of peat mineral mix over TS	20-50 cm of peat mineral mix over TS	20-50 cm of peat mineral mix over TS	> 30 cm of loamy or clayey DP material enriched with organic carbon over TS	> 30 cm of loamy or clayey DP material enriched with low organic carbon over TS	> 30 cm of sandy loam or loamy sand DP material enriched with low organic carbon over TS	100 cm mineral soil slightly enriched with organic matter over TS	100 cm mineral soil slightly enriched with organic matter over TS	> 20 cm of peat mineral mix over > 30 cm of loamy or clayey subsoil over TS	> 20 cm of peat mineral mix over > 30 cm of compacted loamy or clayey subsoil over TS	> 20 cm of peat mineral mix over > 30 cm of sandy loam subsoil over TS	< 20 cm of peat mineral mix over > 30 cm of sandy loam or loamy sand subsoil over TS	20 cm peat mineral mix over 80 cm mineral soil over TS	20 cm peat mineral mix over 80 cm mineral soil over TS
Moisture Regime	mesic	subhydric	subhygric	submesic	subhygric	mesic	submesic	hygric	subhydric	subhygric	mesic	subhygric	mesic	hygric	subhydric
Target Ecosite‡	d,e	g,h	d,e,f	b	g	c	a,b	g,h	l,j,k	d,e	d	d,e,f	d	g,h	l,j,k

† Soil Capability Class, rated from 1 (land having no significant limitations) to 5 (land having severe limitations) in terms of successful forest production

‡ Target Ecosites, as outlined (with moisture regime/nutrient regime) by OSVRC (1998) and GDC (2005) from Beckingham and Archibald (1996).

a = lichen (subxeric/poor)
b = blueberry (submesic/medium)
c = Labrador tea-mesic (mesic/poor)
d = low-bush cranberry (mesic/medium)
e = dogwood (subhygric/rich)
f = horsetail (hygric/rich)
g = Labrador tea-subhygric (subhygric/poor)
h = Labrador tea/horsetail (hygric/medium)
i = bog (subhydric/very poor)
j = poor fen (subhydric medium
k = rich fen (subhydric/rich)
l = marsh (hydric/rich)

Figure 2.4. Soil handling options and related soil capability classification for tailings sand reclamation. [Sources: adapted from OSERN (2003) and OSVRC (1998).]

used in site reclamation is referred to as direct placement (DP) material where the mineral soil is placed on a reclaimed site directly after being stripped; otherwise, it may be placed from a stockpile of suitable material.

The “Land Capability Classification for Forest Ecosystems” (Leskiw, 1998) uses a rating system from Class 1, where lands have no significant limitations for productive forest ecosystems, to Class 5, where lands have severe limitations and no potential for forest ecosystems. Subclasses are used to describe the limitations of the determined classes (Leskiw, 1998). The classification system has two components: the soil and the landscape - each considered separately. The soils are incorporated at a series level. Their classification ratings are related to their productivity, which is controlled by both physical and chemical determinants for the quality of the root zone (OSVRC, 1998). The landscape portion of the rating system incorporates slope steepness, position, aspect, stoniness, and the actual erosion in relation to general tree growth. For example, slope steepness and stoniness less than 30% and 20% respectively are Class 1 while greater than 75% and 80% respectively, are Class 5 (OSVRC, 1998).

The Athabasca oil sands fall within the Central Mixedwood Subregion of the Boreal Forest Natural Region (OSVRC, 1998). Based on ecosystems that naturally occur in the area, the target ecosites that could be supported on the various reclaimed landscapes (Figure 2.3 and 2.4) were limited and identified for each moisture regime (from xeric to hygric) and nutrient status (OSVRC, 1998). These target ecosites should develop similar productivity levels as natural ecosites.

Compared to the natural ecosite, reclaimed soil will tend to have a higher pH (6.5 to 8.0) and salinity (EC of 0.5 to 4.0 dS m^{-1}) in the root zone (OSVRC, 1998). In the various reclamation profiles shown in Figure 2.3 and 2.4, the class ratings assume that the pH of all materials is 7.5 and there are no salinity (EC < 2 dS m^{-1}) or physical limitations, except the overburden which has an EC of 3.5 to 4.5 dS m^{-1}.

2.1.2.1 Saline-sodic overburden

Much of the OB material is from the Clearwater or McMurray Formations, is high in salts and sodium, and often has a low hydraulic conductivity. It cannot be used for reclamation material, but rather, is utilized as a construction material to fill the mined out pits (OSVRC, 1998). Due to its properties, a thicker cap of soil (to 1 m depth) is required as a cover before revegetation begins and is currently the standard procedure. Different reclamation prescriptions have been used over the years and various options are available depending on the quality of the amendment (Figure 2.3).

2.1.2.2 Tailings sand

Tailings sand structures are typically built with lesser slope gradients than SSOB piles (OSVRC, 1998). These materials are usually slightly alkaline as a result of the sodium hydroxide added during the processing, and the organic matter levels are low (OSERN, 2003). The reclamation prescriptions and designated soil type possible from specific profiles assumes no salinity or physical limitations (Figure 2.4).

2.1.3 Certification

The ultimate goal of an oil sands company after reclaiming an area is to have the site certified. Only one site at Syncrude Canada Limited (SCL) was being considered for certification at the time of this research and in March 2008, received certification. This is a new process for the oil sands industries and the forestry companies as well. For certification, the regulatory guidelines must have been met and the revegetation guidelines adhered to. As a result of continually adapting regulations with respect to research findings and monitoring efforts, this process could be more difficult than if one set of rules had existed through the history of the site. When a site meets or exceeds the standards, a certificate is issued which releases the company from its responsibility for the land disturbance and subsequent reclamation (Alberta Environment, 1999). If an area has been successfully reclaimed, it should be a self-sustaining ecosystem with capabilities equal to or better than pre-disturbance levels (OSVRC, 1998).

2.2 Rooting Depths and Distributions

To achieve successful reclamation and attain certification, it is imperative to understand what ecosystems were present before mining began; the mining, extracting, and upgrading processes themselves; the properties of the resultant materials or byproducts that are being reclaimed; and the neighboring ecosystems to which the reclamation is taking place. Knowledge of the structure and functioning of these ecosystems and successional processes and patterns are needed to determine the rehabilitation strategy and extent of human intervention required to ensure the development of a sustainable ecosystem (Wali, 1999). In establishing a new boreal forest ecosystem where drastic soil reconstruction has occurred, part of the necessary information is the structure and functioning of tree root systems and how they may be impacted in the newly developed landscape.

Each tree species has a unique root system to support its structure and to access, store, and transport water and nutrients. The discussion of root systems to follow is based on the terminology described by Wagg (1967) and the different root structures are shown schematically in Figure 2.5. Of particular importance will be the laterals, tap root, sinkers, heart, and oblique roots. The difference between heart and proximal roots are in their origin; heart roots start from the lateral roots near the rootstock, while proximal roots initiate within the rootstock (Wagg, 1967). The typical root forms of the tree species in the boreal forest are shown in Figure 2.6 (Strong and La Roi, 1983b).

2.2.1 Species Effects

2.2.1.1 *Picea glauca* (Moench) Voss (white spruce)

The main root system of wS trees has between four and six primary lateral roots that spread horizontally (Strong and La Roi, 1983b). At the distal portions of each root branch, the fine roots are horizontally oriented, creating a broad root network around the tree base. Descending from the laterals are short oblique root branches or heart roots, which enlarge and elongate with tree age, although to a lesser extent on fine textured soils. Short, fine, branched, obliquely descending roots occur between the heart roots and the first branches of the main laterals. These originate from the sides of the laterals and are thought to play a role in absorption and anchoring functions, increasing in number as the tree grows. Although this lateral dominated root form is typical for white spruce, there are numerous other forms that exist, including an elongated taproot form, restricted taproot form, mono-layered root form and a multi-layered taproot form (Wagg, 1967). Development of a given form is dependent on the soil, site, and stock properties influencing the tree. For example, the restricted taproot form occurs on well drained soils where textural changes occur between horizons or there is compaction of the underlying soil (Wagg, 1967).

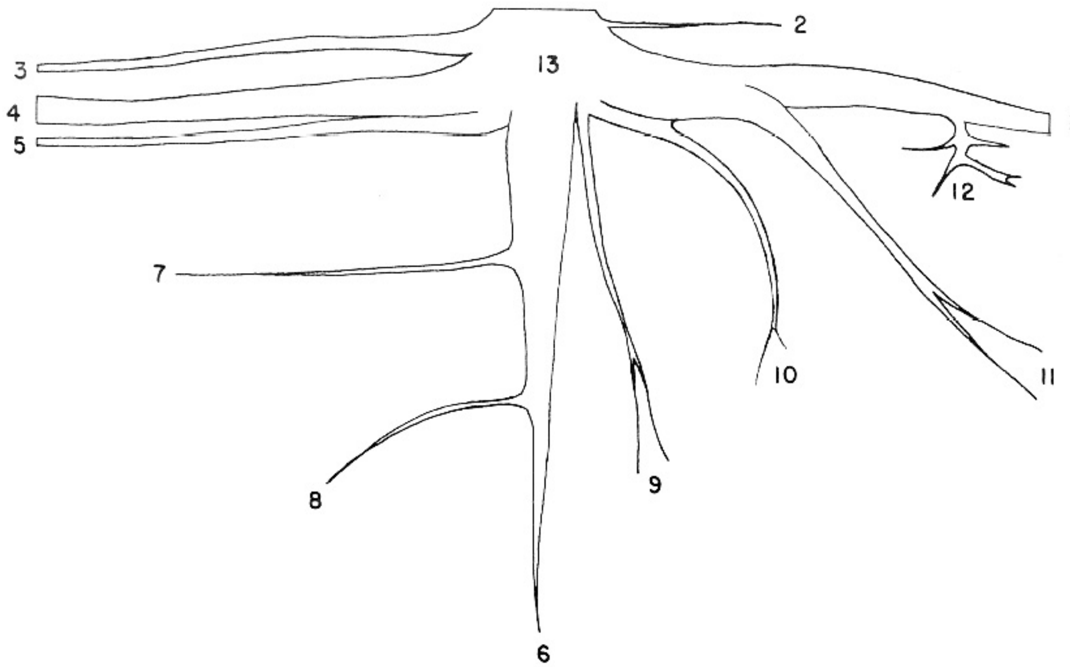


Figure 2.5. Composite root form showing (1) lateral, (2) bur, (3) supralateral, (4) interlateral, (5) infralateral, (6) tap, (7) tap-lateral, (8) tap-oblique, (9) proximal, (10) heart, (11) oblique, (12) sinker, and (13) root-stock. [Source: Wagg, 1967.]

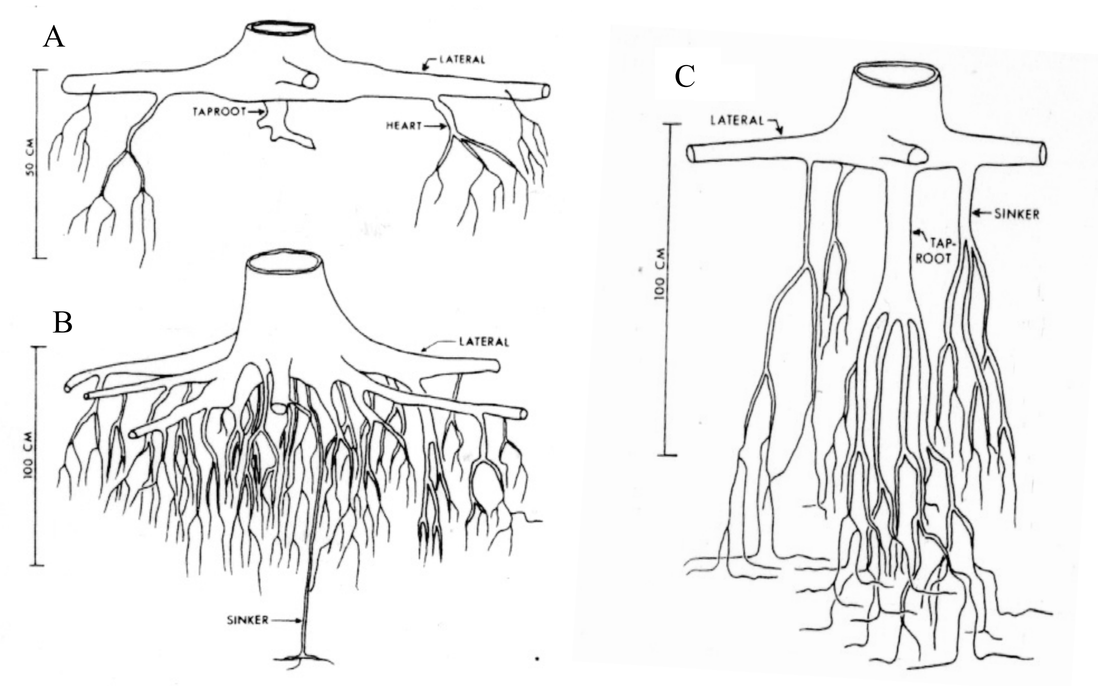


Figure 2.6. Typical root forms of (A) white spruce, (B) aspen, and (C) jack pine. [Source: Adapted from Strong and La Roi, 1983b.]

The typical depth of rooting for wS is between 90 and 120 cm, although sinker roots and taproots may reach a depth of 3 m (Nienstaedt and Zasada, 1990). The majority of the root mass is in the upper 30 cm of the profile with many of the large roots at the organic-mineral soil interface (Nienstaedt and Zasada, 1990).Windthrow can be a problem where the root systems are shallow, less so where a taproot or descending secondary roots have formed. Stone and Kalisz (1991) summarized maximum vertical and radial root growth and indicated rooting depths from 1.4 to 3 m and radial extents of 18.6 and 20 m. Radial growth of trees measured by Strong and La Roi (1983b) averaged 7 m while the lateral spread of trees in Ontario reached 18.5 m, growing at 0.3 m per year (Nienstaedt and Zasada, 1990).

2.2.1.2 *Populus tremuloides* Michx. (trembling aspen)

In a natural aspen stand, lateral roots near the ground surface typically connect the original trees and the suckers. From the tops and sides of the lateral roots, many obliquely ascending fine roots develop (Strong and La Roi, 1983b). Descending lateral roots may develop in addition to sinker roots which typically follow old roots and root channels, especially if a hardpan layer exists (Day, 1944). Lateral root ends may branch out into dense fan shaped mats. These sinkers are thought to provide secure anchorage and access to moisture during periods of drought (Day, 1944; Perala, 1990).

Trembling aspen develops a different root form on sand than on a clay loam soil (Strong and La Roi, 1983b; Day, 1944; Perala, 1990). As the stand ages, a secondary root system develops on both substrates to supplement the primary lateral system (Strong and La Roi, 1983b; Day, 1944). On sand, secondary laterals and sinker roots formed; the laterals descended sharply a distance out from the tree, with little branching; and the sinker roots formed below the base of the tree (Strong and La Roi, 1983b). Highly branched heart roots were found near the base of the tree and numerous short stout roots beneath the base. On clay soil, the laterals spread horizontally to slightly oblique, while the secondary root system consisted of a sphere of short, stout roots below the base of the tree (Strong and La Roi, 1983b).

The shallow lateral component of the tA root system is typically within 15 to 30 cm of the surface while fine feeding roots extend 0.6 to 0.9 m and sinker roots may reach 3 m depth (Strong and La Roi, 1983a; Perala, 1990). Trembling aspen rooting depth increased with age extending to depths of 130 cm when grown on sand; however, when grown on clay loam soils they had a maximum rooting depth of 95 cm (Strong and La Roi, 1983a). Numerous studies summarized by Stone and Kalisz (1991) showed that maximum vertical rooting depth ranged from 1.5 to greater than 3 m, while the radial spread ranged from 14.3 to 30.5 m.

2.2.1.3 Root length densities of mixedwood and pure stands

Van Rees (1997) reported greatest root length at aspen-white spruce mixedwood sites to be from grasses. Older stands showed decreasing root length values for grass and 'other' species as the canopy thickened reducing the light for the understory plants. The maximum root length density for all species occurred in the LFH layer, with the root length density of aspen at 0.5 cm cm^{-3} and wS at 0.75 cm cm^{-3}, while grass root length density in the LFH layer was reported as 27 cm cm^{-3} (Van Rees, 1997). Strong and La Roi (1983a) reported that about 50% of all roots were within a 15 cm zone, generally within 5 cm of the LFH layer. The top 10 cm of the rooting zone had between 11,000 and 30,000 roots m^{-2}, with the maximum at the organic-mineral soil interface. Below 15 cm, the root length densities for all species decreased (Van Rees, 1997; Strong and La Roi, 1983a). Van Rees (1997) found that only 8 to 12% of the total root length to a 120 cm depth was below a 60 cm depth. As the mixedwood stands aged (from 10 to 20 years), the total root biomass for all species increased, decreasing again for the oldest site of 110 years (Van Rees, 1997). Strong and La Roi (1983a) studied aspen and jack pine stands and found that all stands showed decreases in root density with increasing depth and with increasing age of stands, with a maximum rooting depth on coarse-textured soils and a minimum rooting depth on organic soils.

2.2.1.4 *Pinus banksiana* Lamb. (jack pine)

The jP trees examined by Strong and La Roi (1983b) developed four to six primary lateral roots, spreading horizontally within the upper 12 cm of the mineral soil. The majority of jP roots (60 to 95%) are laterals (Rudolph and Laidly, 1990) that together with their secondary branches create ovate root networks when viewed from above (Strong and La Roi, 1983b). Jack pine trees have large taproots that were found to a depth of 1.3 m on average, extending down to a maximum of 2 m. Rudolph and Laidly

(1990), report rooting to depths below 2.7 m on deep, well-drained soils. Branching of the taproot into smaller descending roots begins between 50 and 90 cm (Strong and La Roi, 1983b). If sufficient moisture is present at depth, these roots may branch again, but will then spread horizontally. Numerous cylindrical sinker roots (usually less than 10 per tree) develop, most growing near the stump to a similar depth and with a similar branching habit as the taproot. Trees older than 30 years also had 'herring bone' roots in the stump area of the tree. These roots taper as they descend vertically into a single plane of short (less than 2 cm) closely spaced secondary branches (Strong and La Roi, 1983b).

In older stands, the vertical root component is often less than 3%, increasing up to 26% for younger stands (Strong and La Roi, 1983b). About 50% of all roots are within a 15 cm zone, generally within 5 cm of the LFH layer (Strong and La Roi, 1983a). Maximum depths recorded for jP are from 1.0 to 2.9 m while the range for the maximum radius is 8.5 to 14.0 m (Stone and Kalisz, 1991).

Jack pine grows best on acid, sandy soils with small amounts of Ca and Mg (Klinka, 2002). With its taproot system, it is able to tolerate water and nutrient deficient soils. Alkaline soils and Ca-rich soils have a negative impact on jP production (Klinka, 2002).

2.2.1.5 Volunteer species

Other species commonly found growing on the reclamation sites near Fort McMurray include fireweed [*Chamerion angustifolium* (L.) Holub], clover [*Melilotus* (L.)], grasses, sow thistle (*Sonchas oleraceus* L.), balsam poplar (*Populus balsamifera* L.), and willow (*Salix* L.). Fireweed has a fibrous root system and extensive rhizomes for reproduction. Perennial sow thistle has a root system up to 3 m deep and extends horizontally below the cultivation zone with rhizomes near 60 cm depth (Royer and Dickinson, 1999). Yellow and white sweet clovers have root systems up to 1.2 m deep (Royer and Dickinson, 1999). Grasses have fibrous root systems, the depth and distribution varying with the species. *Salix* L. species have been reported to develop roots to depths greater than 3.5 m with radial extents from 6 to 40 m (Stone and Kalisz, 1991). Balsam poplar has a root system similar to that of tA.

2.2.2 Soil Property Effects

The belowground root form of a tree is distinguishable from other species, just as the aboveground form of a tree is identifiable due to its inherent genetics (Gale and Grigal, 1987). This means that the typical root forms discussed previously will develop under normal conditions. If root growth is limited by some other factor, deviations from these typical forms may occur.

The growth and morphology of roots and root hairs are susceptible to mineral excesses or deficiencies (Baligar et al., 1998). The root:shoot ratio may be altered, or the length, thickness, surface area, or density of roots can change as a result of these extremes. A nutrient deficiency typically means the roots become finer, while a heavy metal toxicity might be suggested by the initiation or growth of second and third order lateral roots, while the tap roots and first order laterals are negatively impacted (Baligar et al., 1998). At SCL's Mildred Lake mine site, there is the potential for salinity, sodicity or pH to influence the rooting of boreal species due to the presence of high salt and sodium concentrations in the overburden material. Haul trucks (up to 635 tonnes) transporting the material may compact the soil, which could also be limiting to root growth.

2.2.2.1 Compaction

It is through the presence of pores or voids that water or air enters the soil and it is the size of these pores which determines how easily roots can grow or expand with only small pressures. Compaction can reduce this pore volume, thus decreasing water and gas exchange and creating greater resistance or impedance to root extension (Russell, 1977; Singh and Sainju, 1998). Roots cannot penetrate rigid pores with a smaller diameter than the extending portion of the root and will increase in diameter when restricted by external pressure (Russell, 1977; Singh and Sainju, 1998). Although roots can exert maximum pressures, or root growth pressure (RGP), of 0.9 to 1.3 MPa, smaller pressures of 0.025 to 0.05 MPa can cause a large reduction in root extension (Russell, 1977) and abundant growth of root hairs. When the pore size is intermediate between that of the root axes and laterals, the laterals proliferate (Russell, 1977).

Bulk density and soil resistance are important soil characteristics that can be used indirectly to determine how soil porosity has changed (Russell, 1977). As bulk density increases, porosity decreases and root penetration is restricted (Singh and Sainju, 1998). Bulk densities greater than 1.5 g cm^{-3} in fine-textured soils or 1.7 g cm^{-3} in coarse-textured soils usually restrict root growth (Lyle, 1987). Penetrometers mimic root apices displacing soil particles to estimate the forces that resist root growth and provide a relative measure that can be related to root extension (Russell, 1977). Unger and Kaspar (1994) found that root growth was slowed considerably or ceased when penetrometer resistance was greater than 2.0 MPa. Water content affects soil strength, creating greater mechanical impedance as water content decreases.

It has been suggested that even if root extension is restricted, a crop's production may not be hampered provided the supply of water and nutrients is not reduced. For tree productivity, however, the anchorage provided by the root system is necessary to prevent windthrow. Each species has a different ability to penetrate compacted layers within or throughout the soil profile (Singh and Sainju, 1998). Restricted root growth could reduce tree stability and result in higher production losses.

2.2.2.2 Salinity

Saline soils commonly contain chlorides and sulfates of Na, Ca, and Mg (Baligar et al., 1998). Salinity can reduce water and nutrient uptake by imposing an osmotic and ionic stress on the roots (Baligar et al., 1998). This change in osmotic potential can cause soils, for example, high in Na, to depress the absorption of other cations (Russell, 1977). Different species are susceptible at different levels, but typically less roots form and laterals die back (Baligar et al., 1998) while the plant itself is stunted (Jurinak et al., 1987). Necroses in the buds, roots, leaf margins and shoot tips are also common in woody species (Howat, 2000). Generally, levels of salts and Na at or in excess of an electrical conductivity (EC) of 4 dS m^{-1} or a sodium absorption ratio (SAR) of 15 are considered harmful to plants (Howat, 2000). This is a basic statement that is not true of all species and does not take into account the different types of ions that may be present. As Howat (2000) reported, jack pine seedlings are more susceptible to NaCl at 6 dS m^{-1} than $NaSO_4$ at 10.5 dS m^{-1}. Differences in salt tolerance levels also exist between tree seedlings and mature stands of the same species.

The overburden material at Syncrude is high in salts having an EC between 4 and 11 dS m^{-1} while the undisturbed soils nearby range between 0.32 and 1.03 dS m^{-1} in the surface organic layers and from 0.06 to 0.33 dS m^{-1} in the top 10 cm of the mineral soil (Howat, 2000).

2.2.2.3 Sodicity and pH

Besides typically having excess $NaHCO_3$ and exchangeable Na, alkaline soils can lead to toxicities in Na, Mo, B, and Se (Baligar et al., 1998). Soils are considered sodic or alkali when pH is above 8 and SAR is 15 or greater (Howat, 2000). With sodicity, a higher pH value is expected which can directly or indirectly cause a decrease in root mass, length, and root hair formation (Baligar et al., 1998). Higher pH values can influence the availability of nutrients to the plant (Tucker et al., 1987). At pH levels above 9, OH^- ions can limit water uptake also reducing growth. Sodium also leads to deterioration of the soil structure and its hydraulic conductivity (Plaut et al., 1997). Hydraulic conductivity can be maintained if concentrations of electrolytes are present above a threshold level. For example, a soil with an SAR of 20 to 25 would require an EC of 1 to 2 dS m^{-1} (Jurinak et al., 1987). At an SAR of 10 and an EC of only 0.3 dS m^{-1}, clay dispersion blocks the pores and reduces permeability (Jurinak et al., 1987). The result can be a hardpan layer, nearly impervious to water and roots. Root growth on sodic spoils with a cover soil is limited by the low hydraulic conductivity of the medium which restricts water uptake by plant roots (Carlstrom et al., 1987). Because reclaimed soils place non-saline, non-sodic soil over the SSOB, there is the potential for salts and Na to slowly migrate up via diffusion into the cover material if the spoil is dispersive with a low hydraulic conductivity and an SAR above 20 (Carlstrom et al., 1987). A dispersive soil is structurally unstable due to excessive exchangeable Na, allowing clay particles to disperse easily and aggregates to break down when wetted (Holm and Henry, 1982).

Although solonetzic soils (Joslyn series) have been identified near Fort McMurray, the occurrence of saline soils in the boreal forest is uncommon (Howat, 2000). Alkaline soils exist in the Hinton area of Alberta, likely the result of calcareous loess deposits (Howat, 2000). Purdy et al. (2005) studied naturally saline forest ecosystems in Alberta and examined changes in vegetation and soils along transects from wetland to upland areas. When salinity was limited to depths of 80 to 100 cm, similar vegetation to natural non-saline forest ecosystems existed.

2.3 Root Activity

One of the main functions of tree roots is to take up water and nutrients. This is measured as the activity of the roots (Van Rees, 1997). Higher levels of uptake indicate more active roots and low to no uptake of nutrients or water occurs in inactive roots.

2.3.1 Tracers and Measurement

Root activity is often measured either by stable or by radioactive isotopes. One such stable isotope is strontium (Sr). Strontium is naturally present in the earth's crustal rocks at an average of 370 mg kg^{-1}, but has a large range from 1 mg kg^{-1} to several percent (Capo et al., 1998). In soils, a concentration of 240 mg kg^{-1} is average, but it may be below 10 mg kg^{-1} or above 1000 mg kg^{-1} at times. Strontium is a divalent alkaline earth element with an ionic radius (1.18 Å, 0.099 nm) close to that of calcium (Ca) (1.00 Å, 0.113 nm) (Capo et al., 1998; Poszwa et al., 2000). They are so similar in size that Sr substitutes for Ca in minerals such as plagioclase feldspar, apatite, sulfates (gypsum and anhydrite), and carbonates (calcite, dolomite, and aragonite). In soil, the divalent cations are more strongly retained (Ba > Sr > Ca > Mg) than monovalent cations. A successful tracer must have low background concentrations in the soil, be of little significance as a nutrient and be non-toxic to the plant (Pinkerton and Simpson, 1979; Capo et al., 1998). As a stable tracer, Sr is strongly held by the soil, remaining in the area where it is applied unless physically moved (Van Rees, 1997). Vegetation takes up Sr much like it would Ca off of the exchange complex of organic matter or clay and from soil solution and incorporates the Sr into the tissues. Vegetation may contain from a few μg g^{-1} in roots and leaves to 2000 μg g^{-1} in the wood of some samples (Capo et al., 1998).

2.3.2 Influencing Factors

Different tree species have different root forms that will access water and nutrients at different depths. As a result, the uptake of Sr will vary. Root growth will also be initiated and end at different times of the year as a response to soil temperature and species effect. Through the use of $SrCl_2$, Mamolos and Veresoglou (2000) were able to determine the temporal pattern of root growth and the deepest rooting species at their site. It is not always desirable to know when the roots are actively growing, but rather just overall uptake for depth interpretations. These interpretations must take into account the differences in soil horizons (i.e., texture, thickness, structure, etc.). For example, consideration of a hardpan layer at one location and another site with a coarse textured soil will likely yield different results. For a reclaimed soil, the depth to overburden and its composition are important factors to examine in the interpretation of rooting depth and activity. Poszwa et al. (2000) concluded in their study that for spruce trees (*Picea abies* L., Karst), Ca was preferentially taken up over Sr on acid soils, while Sr was preferential to Ca on calcareous soils. This was not true for beech trees (*Fagus sylvatica* L.). They also concluded that Ca is preferentially translocated from roots to leaves over Sr, but again this varies with the tree species. Overall, Sr has been recognized as a good indicator of root activity.

2.4 Planted Jack Pine Root Development, Form and Structure

How a root form will develop once a seedling is planted out into the field is not limited to the above species or soil factors (Sections 2.2.1 and 2.2.2). Other factors such as stock type and planting technique can create serious deformities in the root systems of planted trees. These deformities may limit the uptake of water and nutrients, the production of photosynthates, and reduce stability (Sutton, 1978). The reduced root area with increased deformities decreases tree stability (Grene, 1978).

2.4.1 Typical Deformities

Tap roots develop at the earliest stage of growth and first order laterals emerge from the taproot (Persson, 2002). Some species such as *Picea abies* (Norway spruce) react strongly to minor movements of its taproot during early growth resulting in impeded root development (Puhe, 2003). Nursery practices and planting of tree seedlings out into the field may cause root damage that could limit growth. Typically, root systems are more severely deformed when they are planted compared to natural regeneration from seed (Puhe, 2003; Sutton, 1969). The extent of the root deformity will vary with the influences of the initial tree root system, the planting method, site conditions, and care taken in planting the seedling (Puhe, 2003). Grene (1978) answers the question of how root deformation affects performance after planting. Productivity is generally satisfactory until late in a stand's life when problems such as failing stability are noticed. The persistence of reduced root area, which has a high correlation with tree stability, was noted for years after planting (Grene, 1978). This often occurs on large scales because large areas are planted with the same stock or using the same planting technique. Research by Gillgren (1971) as cited in Grene (1978) showed that although some damages may be long-lasting, the frequency of damaged roots slowly decreases as age increases. This suggests that deformities that were once visually apparent have been outgrown.

Common deformities of root systems are kinking and coiling of roots. Segaran et al. (1978b) provide a good description of the rating system they used to evaluate the roots of excavated trees. Coiling or spiraling refers to the wrapping of roots around the tree stem while kinking refers to the degree and number of bends in the roots, typically at 90° angles (Segaran et al., 1978b; Preisig et al., 1978; Bailey, 2002). Another common type of deformity seen in the field is that of L- or J-rooting. In these cases the roots are bent upwards forming an L or J shape. The root system may also maintain a high resemblance to the original container or stock type from when they were grown in the nursery and planted out. This may impact how well the roots are distributed in the soil around the tree (symmetry) and if a taproot actually develops.

2.4.2 Possible Causes of Root Deformities

Vertical root development is important in reducing windthrow susceptibility (Puhe, 2003). Limiting factors for deeper root growth include shallow bedrock, clay-rich B horizons, shallow compacted or hardened soil horizons, close to surface ground water, stagnant water, and toxicity (Puhe, 2003). These are potential natural sources for limiting vertical root development which tends to just lead to other typical root forms developing such as those mentioned for wS in Section 2.2.1. They do not explain the spiraling, kinking, grafting, asymmetrical and oddly shaped root systems that are often found on planted sites.

2.4.2.1 Stock type

In terms of production, Hellum (1978) found that both bareroot and container grown stock types did not compare with the naturally generated seedling. Segaran et al.

(1978b) compared paperpot to bareroot and naturally regenerated jack pine using a rating scale for the degree of spiraling and resemblance of root form to the container shape. The majority of outplanted bareroot stock had L- or J-shaped root systems, the result of poor planting technique. The number of grafted roots increased with age of the stand. The longer a plant is kept in any container before planting, the greater the number of root deformities (Jansson, 1971 as cited by Grene, 1978). This can be relieved by pruning the deformed roots prior to planting (Harris et al., 1973 as cited by Grene, 1978).

2.4.2.2 Planting techniques

Some of the many possible results of planting observed in the field are illustrated and discussed by Huuri (1978). Planting technique is an overriding cause of many root deformities. Even if the stock type has some influence on the resultant root structure of the tree, improper planting technique could determine the final root form. Some of the potential planting problems include planting too deeply or too shallowly, horizontally or at an angle, with the root tips exposed on the surface, roots covered with non-mineral soil, or rolled into a ball (Huuri, 1978; Paterson and Maki, 1994). Typically, the most common issue is folding, wrapping, balling, or bending the roots to get the tree seedling into the ground. This results in J- or L-shaped root systems (sometimes S-). If the roots were balled up or wrapped around prior to planting, they tend to keep that structure. Correct planting techniques are described by Segaran et al. (1978b).

These deformities may restrict root growth and consequently hamper tree productivity. Additionally, if proper anchorage is not established, tree survival could be reduced. Planting technique is critical to the future of tree seedling development as any deformity created is a persistent part of the root system structure.

3 VERTICAL ROOT DISTRIBUTIONS FOR BOREAL MIXEDWOOD STANDS PLANTED ON RECLAIMED SALINE-SODIC OVERBURDEN

3.1 Introduction

The Athabasca oil sands deposit is located in northeastern Alberta within the boreal forest region. Here, among the mixedwood upland forests of trembling aspen (tA; *Populus tremuloides* Michx.) and white spruce (wS; *Picea glauca* (Moench) Voss) is where Syncrude Canada Limited (SCL) has its leases. Before the oil sands are mined, the trees are harvested, the land is drained if necessary, and the peat and upper mineral soil are salvaged for later use in the reclamation process. At the SCL Mildred Lake mine site, a highly saline-sodic, marine clay-shale formation is found below the salvageable mineral soil and above the oil sands. This material in particular, and often some of the lean oil sands (i.e., sands with bitumen content insufficient for economic extraction), is referred to as overburden (OB) for the purposes of this paper, and is used to backfill the mined-out pit and construct a new upland landscape.

The mined area must be reconstructed to form a landscape designed to incorporate the required slopes for hydrologic processes and the necessary cover thickness and soil quality to support forest growth. Because of their inherent properties (salinity, sodicity, and low hydraulic conductivity), OB slopes are constructed with grades to allow for movement of salts and are usually designed to support upland forest species. The salvaged peat and mineral soil are utilized in the capping or covering of the constructed landscape. Generally, the reclamation of saline-sodic overburden (SSOB) requires 1 m of mineral soil or a peat-mineral mix to be placed over the OB material. Once reclaimed, a site is planted with tree seedlings native to the boreal forest ecosystem.

At the SCL Mildred Lake mine site, salts and sodium from the SSOB slowly migrate upwards via diffusion into the non-saline, non-sodic cover material (Kessler, 2007; Kelln et al., 2006). Carlstrom et al. (1987) noted that soils with a low hydraulic conductivity and a sodium absorption ratio (SAR) above 20 have the potential for upward salt diffusion. Many boreal forest species are not tolerant of salinity (Howat, 2000) and the growth and morphology of roots and root hairs can be susceptible to salt excesses (Baligar et al., 1998). Additionally, haul trucks (weighing up to 635 tonnes) transporting the reclamation material can compact the cover material which reduces the soil pore volume resulting in greater resistance or impedance to root extension (Singh and Sainju, 1998). However, it is not known if the SSOB will affect the rooting distribution of the new planted boreal species and how the SSOB will impact the long-term health and productivity of the planted forest. The objectives of this study, therefore, were to examine selected characteristics of the reconstructed soil profile and determine their significance in relation to the root length density distribution within the cover and SSOB. The null hypothesis was that root length density distributions were not influenced by the SSOB.

3.2 Material and Methods

All sites were located on reclaimed landscapes at the SCL Mildred Lake Mine site, approximately 40 km north of Fort McMurray, Alberta, Canada. The mean annual temperature is 0.7°C with an average January temperature of -18.8°C and average July temperature of 16.8°C, based on climate data for the period 1971 to 2000 (Environment Canada, 2005). The mean annual precipitation is 455.5 mm with 342.2 and 155.8 mm as rainfall and snowfall, respectively (Appendix A).

3.2.1 Site Descriptions

This study was conducted on three different sites with mixedwood stands (tA and wS) planted on reclaimed saline-sodic overburden (SSOB) in 2000 (SW30) and 1992 (S2), and on non-saline-sodic OB in 1990 (S4).

3.2.1.1 SW30

SW30 is the youngest site where placement of the SSOB material was completed in 1998 and the cover material was added in 1999 for each of the prototype covers (Meier and Barbour, 2002). Only the D3 prototype cover (100 cm cover consisting of 80 cm of mineral soil direct placed on the SSOB with a 20 cm cap of peat on top) was used for this study. White spruce and tA seedlings (ratio unknown) were planted in August 2000 (2000 stems ha^{-1}). The site is approximately 1 ha in size with a 5:1 north-facing slope (Meier and Barbour, 2002).

3.2.1.2 S2 south

The south facing slope of S2 was divided into two sections each capped with different material. In 1991, the west portion of the slope (including the area for this study) was capped with 109 cm (measured to be 90 cm) of material directly placed. In 1992, the site was planted to tA and wS at a 2:1 ratio with a target density of 2000 stems ha^{-1}. The area was further underplanted with both species in 2002 to achieve the target density (J. Pumphrey, personal communication, 2004).

3.2.1.3 S4

The capping of S4 was completed in 1990. The 42 ha site was covered with 184 cm of material from the S4 stockpile (a mixture of peat and mineral soil with the latter often of poor quality for reclamation and originally considered as waste material). This area has 6:1 north facing slopes and planting of tA and wS was completed in 1990 using a target density of 2261 stems ha^{-1}. The relative proportion of each species was not available.

3.2.2 Field Methods

In order to determine the vertical root length density distribution for each site, three transects were set up parallel with the slope direction, approximately equidistant from each other at a distance based on the size of the site. The variations in slope and site construction material were accounted for by taking four approximately equidistant points along the transects (upper slope, mid-slope 1, mid-slope 2, lower slope). The first sampling point was taken at a distance determined randomly between 5 and 20 m. The distance between the remaining sampling points was based on the size of the site and the length of the slopes (north-south distances were approximately 45, 30, and 25 m while east-west distances were 12, 120, and 30 m for the SW30, S2, and S4 sites, respectively). Appendix B provides site maps for each location with transects and sampling designs as well as GPS locations for all sample points.

To examine the microsite variables and the possible effects of salt and sodium migration on root distributions, the depth of sampling was chosen to include a complete sample from the OB material at each site. Root cores (Oliveira et al., 2000) were collected from 12 locations at each site using a bucket auger (6.6 cm diameter) at 15 cm increments and stored in plastic bags. Water was added to each sample upon returning from the field and soaked overnight in a cooler before being frozen to prevent root degradation. The freezing and thawing cycle aids in the removal of clay during the root washing process (Van Rees, 1997).

Roots were washed in 1 mm mesh screen submerged in a bucket of water and slightly agitated until all the soil was removed (Van Rees and Jackson, 1994; Oliveira et al., 2000). Live roots were picked out and rinsed again. In all cases, the water was poured through a second screen to recover any fine roots that had been dislodged into the wash bucket during the washing process. Root samples were blotted dry, placed in plastic bags and kept frozen until further analysis was required.

Soil composite samples were collected at the same time as the root samples from the same sampling points and depths. These samples were collected using a ratchet auger except where rocks became a problem and for depths beyond the reach of the auger. Typically, three or four samples from near the root core were obtained to make a composite sample. At times, rock obstructions required extra sampling with the bucket auger to obtain root cores. When this occurred, the unused core increment was taken as a soil sample instead of collecting a composite sample. For the depths where neither of the above two options occurred (usually quite deep in the profile), the root core was sub-sampled at the time of washing. Sub-sampling meant that the soil was collected from the core while carefully checking for and removing any roots from the sub-sample. The remainder of the root core was then washed as previously described to obtain the roots and the soil samples were allowed to air-dry in the greenhouse.

Soil pits were excavated at the SW30 and S2 South sites in the upper, mid-, and lower slope positions along the second transect to collect samples for determining bulk density (as shown in Appendix B). Pits were not dug at S4 due to the greater depth required. The depth to overburden was recorded for each pit and the depth of peat if applicable. Steel rings (i.d. 5 cm; height 5 cm) were used to collect equivalent volumes of soil from each 15 cm depth increment to the depth of OB and a complete sample from the OB material. The rings were placed horizontally and hammered in with a rubber mallet to obtain samples from one vertical wall of the pit. These soil samples were weighed wet then oven-dried at 105°C for 48 hours. Bulk density was determined as mass of dry soil per unit volume (steel ring volume).

Soil resistance was measured to a 50 cm depth using a recording cone penetrometer (Eijkelkamp, Netherlands) with a base surface cone of 1 cm^2. Resistance was recorded for each 5 cm increment at each of the sample locations at all sites.

Composition of understory species at each sampling point was recorded at the time of sampling. Percentage cover for each species was recorded the following year using a 1 m^2 quadrat. The distances to, and the species of, the nearest trees were recorded at this time, counting each stem as a separate tree without checking for joined root systems.

3.2.3 Laboratory Methods

Composite soil samples were air-dried, ground, and sieved (2 mm). Electrical conductivity (EC) and pH were determined for all samples using the 1:2 soil to water dilution ratio method (Rhoades, 1996; Thomas, 1996) with a Conductivity Meter Type CDM2e (Radiometer Copenhagen, Denmark) and a Corning pH meter 120 (Corning Inc., New York), respectively. The 1:2 dilution method was used because of its ease, rapid extraction time, and consistency (Hogg and Henry, 1984); however, the standard test for saline and sodic soil or overburden is the saturated paste method (Tucker et al., 1987). Saturated pastes account for texture as each soil is brought to an equally wetted state (field capacity), and thus, are more representative of field conditions than a diluted ratio (Tucker et al., 1987). The saturated paste method was used for randomly selected samples from all sites and all textures of soil, allowing for a full range of EC values. Conductivity values of the extracts from both the saturated paste and the 1:2 dilution methods were plotted against each other to obtain a linear relationship (Hogg and Henry, 1984). The resultant r^2 value and the regression equation for the fitted line are as follows:

$$EC_{SPE} = 1.4006 * EC_{1:2} + 0.5667 \qquad (r^2 = 0.9433, n = 54) \qquad [3.1]$$

where EC_{SPE} and $EC_{1:2}$ are the electrical conductivity (EC) values obtained using the saturated paste extract (SPE) and dilution methods (1:2), respectively.

Soil extracts (from both extraction methods) were analyzed for soluble cations by atomic absorption (Ca and Mg) and flame emission (K and Na) on a Varian SpectrAA-220 spectrometer (Varian Australia Pty Ltd., Australia) equipped with a SPS 5 Sample

Preparation System. Samples were analyzed according to standard procedures (Varian, 1989).

The SAR values calculated from the SPE method were compared to the values obtained for the same samples using the diluted ratio method (Hogg and Henry, 1984) resulting in the regression equation:

$$SAR_{SPE} = 1.3444 * SAR_{1:2} + 0.4766 \qquad (r^2 = 0.9855, n = 54) \qquad [3.2]$$

where SAR_{SPE} and $SAR_{1:2}$ are the values obtained using the saturated paste extract and dilution methods, respectively.

Equations 3.1 and 3.2 were used to calculate the EC and SAR, respectively, for the remaining samples to present all the data obtained by 1:2 dilution ratio method as SPE values.

The washed root samples were divided into diameter classes (<1 mm, 1-2 mm, 2-5 mm, >5 mm) and the <1 mm diameter class scanned to determine root length. All other roots (diameters $\geq$ 1 mm) were hand-measured for length. Random root samples of the < 1 mm class were selected, spread out on acetate sheets, and scanned (360 dpi) to determine root length using root length determination software (Berntson, 1992; 1997). Samples from SW30 were dyed with methyl violet (0.5 g methyl violet in 50 mL of 1% ethyl alcohol) prior to scanning (Richner, et al., 2000; Harris and Campbell, 1989). The dye enhanced root visibility by creating a greater contrast between the light background and the roots. Root samples were then oven-dried at 65°C for 48 h and weighed. Separate linear regression relationships (with zero intercepts) between dry weight and root length were used for SW30 (r^2 = 0.92), S2 (r^2 = 0.99), and S4 (r^2 = 0.99) to calculate the root length for all remaining samples. The regression equations, r^2 values, and number of samples used in the regression for each site are presented in Appendix C.

3.2.4 Statistical Analysis

All statistical analyses were performed using SPSS Versions 13 and 14 (Chicago, Illinois). The root length density (RLD) data was transformed using the log-transformation described by McCune and Grace (2002), hereby referred to as the minimal log-transformation. It preserves the order of magnitude present in the data, often lost by the common procedure of adding one, and results in zero when the initial value is zero. It also produced only positive values for all non-zero data. Root length density was calculated for the upper 30 cm of the soil profile (RLD_u) as not all profiles could be measured to the same depth (due to variation in cover thickness) and because most roots typically occurred in the top 30 cm of the soil profile. For correlation analyses of RLD_u at a given sample location with percent cover, slope position, and number of trees within a 2 m radius, the RLD_u values were log-transformed in the regular manner as there were no zeroes in the data set.

Correlation analyses were performed separately for each site using the minimal log-transformed RLD data, slope position, depth, and seven soil variables (pH, SAR, EC, and soluble Ca, Mg, Na, K). To approximate a normal distribution, the soil variables were all log-transformed for SW30 and S2 prior to analysis. For S4, only K required log-transformation. Average depth was later controlled for in partial correlation analyses. This allowed us to examine the relationships between variables while accounting for or ruling out their relationship with average depth.

3.3 Results

3.3.1 Soil

3.3.1.1 Cover thickness and slope position

Average cover thicknesses for SW30, S2 South, and S4 were 125 ± 22, 80 ± 20 and 150 ± 26 cm, respectively (Figure 3.1). At SW30, mean cover thickness decreased down slope and ranged from 155 ± 9 cm at the upper slope to 110 ± 9 cm at the lower slope. The mid-slope positions at SW30 also had thinner cover than the upper slope. The opposite trend, however, was observed at S4 where the upper slope (140 ± 14 cm) had a thinner cover compared to the lower slope (188 ± 39 cm). Cover thickness at S2 was relatively uniform across slope positions and ranged from 68 ± 6 to 87 ± 38 cm. These differences in cover thickness made it difficult to compare the root distributions, thus, the data was examined in terms of depth from the surface which is the reference point of most importance for roots growing in the profile. All soil data is also presented in Appendix D with the interface layer (the boundary between the SSOB and the cover) as the zero reference point.

At SW30, the thickness of the peat layer measured in the bulk density pits decreased with slope position from 28 cm at the upper slope to 20 and 17 cm at the mid-

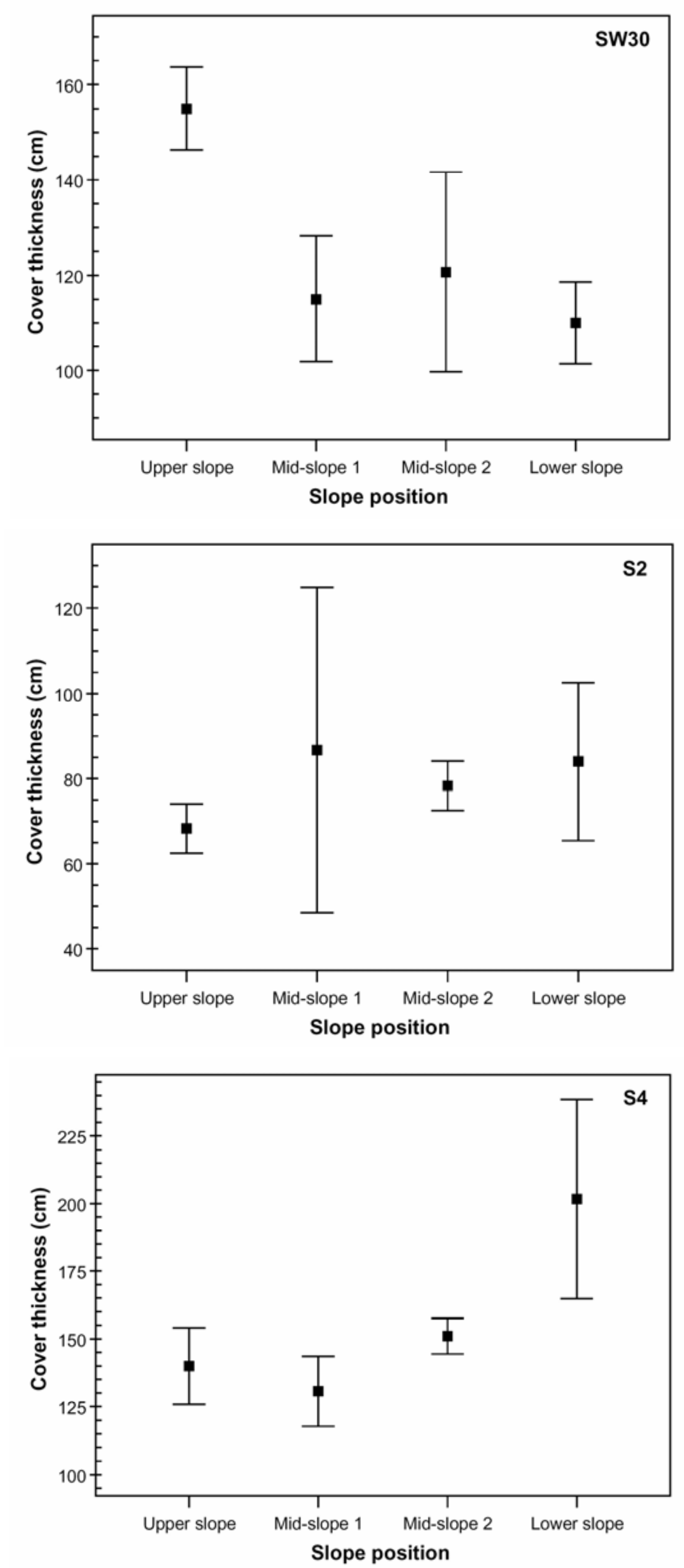


Figure 3.1. Mean cover thickness for each slope position (n=4) at each reclaimed site. Error bars are ±1 standard deviation (SD).

and lower slopes, respectively. Depth to the interface layer also varied and cover thickness was measured to be 106, 110, and 75 cm in the upper, mid- and lower slope positions, respectively. At S2, there was no peat layer, and cover thickness was 106, 75, and 95 cm for the upper, mid-, and lower slope positions, respectively.

3.3.1.2 Bulk density and resistance

Bulk density was determined from the soil profile samples collected at SW30 and S2 for each slope position. The peat layer at SW30 had the lowest bulk density (0.2 g cm^{-3}) while the highest was measured in the cover soil material (1.7 g cm^{-3}) (Figure 3.2). Bulk density at SW30 ranged from 0.2 to 0.4 g cm^{-3} in the peat, 1.2 to 1.7 g cm^{-3} in the cover soil, and 1.4 to 1.5 g cm^{-3} in the SSOB and all slope positions had similar values. At S2, although the spread of bulk density values for the secondary soil material was similar to SW30, it was shifted slightly higher (1.5 to 1.9 g cm^{-3}). The soil bulk density profiles at S2 were more variable between slope positions compared to SW30 with values ranging from 1.5 to 1.9 g cm^{-3}. The lower slope position, however, had a bulk density of 1.3 g cm^{-3} in the OB.

Resistance measurements recorded with the cone penetrometer at SW30 and S4 were taken within two days of each other (June 14 and 16, 2004) when soil moisture was not limiting, while the measurements at S2 were taken approximately three weeks later (July 8, 2004) after nearly a month without rain. Volumetric water content of the secondary material determined from the bulk density samples collected in 2003 was nearly 13 percent lower at S2 than at SW30 when sampled within a ten-day period when rain was not limited. As a result of differences in soil volumetric water content and the relationship with soil resistance, the comparability between sites is reduced. However, as bulk density samples were not collected for S4, the resistance measurements give some relative indication of root penetrability.

The recording cone penetrometer scale measures a maximum of 5 MPa. This value was exceeded before reaching a 35 cm depth at all but one sample location for S2 (Figure 3.3). Seventy-five percent of the sample points recorded 5 MPa by 25 cm depth at this site. At S4, only four of the 12 sample locations had values reaching or exceeding 4 MPa by the 50 cm depth, while only two of the sample locations at SW30 exceeded 3.8 MPa within the same 50 cm depth.

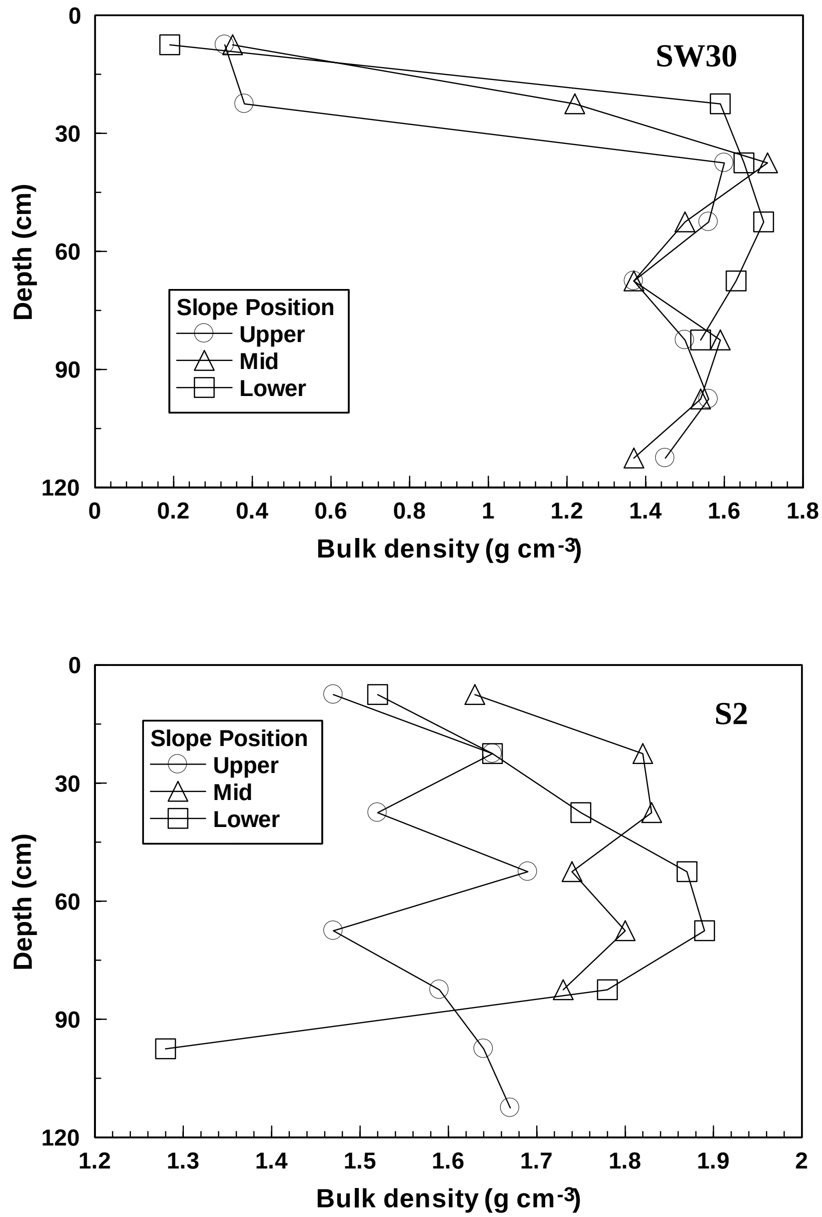


Figure 3.2. Bulk density values at 15 cm increments for upper, mid-, and lower slope positions at SW30 and S2.

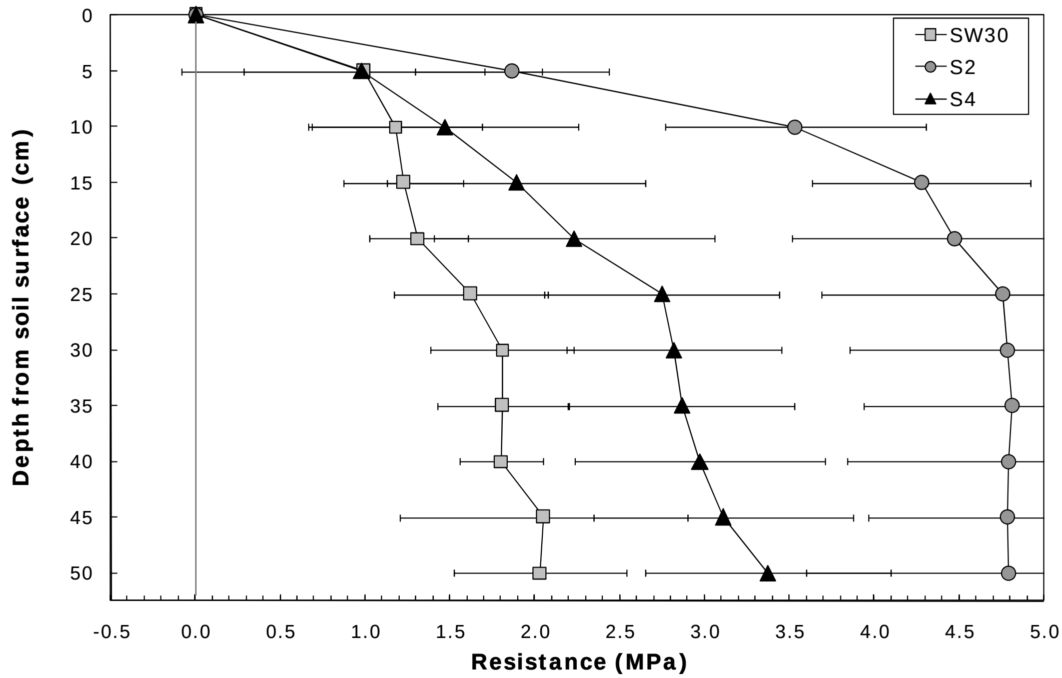


Figure 3.3. Mean soil resistance for all slope positions at SW30, S2, and S4 (n=12). Error bars are ±1 SD.

Soil resistance readings were lowest for the SW30 site, reaching a maximum of 2.0 MPa at a 50 cm depth (Figure 3.3). At S4, soil resistance readings were similar to SW30 in the surface (0-10 cm depth), but were about 1.3 MPa higher than SW30 between 25 and 50 cm depth. The S2 site had the highest soil resistance readings at all depths, reaching a maximum value of 4.8 MPa at 25-50 cm in the profile.

3.3.1.3 Soil pH and soluble cations

At SW30, pH values were lowest for the surface peat layer (mean 6.6 ± 0.5) and near neutral (7.1-7.5) in the cover soil, and then into the OB (Table 3.1). Peat samples with the lowest pH occurred at the upper and lower slope positions which coincided with greater depths of peat (data not shown). At S2, the mean pH ranged from 7.0 to 7.3 in the cover soil and then decreased in the SSOB to a low of 6.1 at the 120 cm depth (Table 3.2). At S4, peat was mixed into the cover material resulting in slightly lower pH values compared to the other two sites, but remained fairly constant with depth (Table 3.3).

Generally, soluble cation concentrations increased just before the interface layer (Appendix D) and into the overburden at SW30 (Table 3.1) and S2 (Table 3.2). This trend was not observed at S4 where concentrations generally were the same with increasing soil depth (Table 3.3).

Calcium levels at S4 (Table 3.3) were nearly 10 times higher than the values observed in the cover soil at SW30 (Table 3.1) and S2 (Table 3.2). However, Ca levels from the interface and into the SSOB at SW30, and into the cover soil at S2 were near or had reached the Ca concentration levels observed throughout the profiles at S4 (Table 3.3 and Appendix D).

Soluble Mg and K levels in the cover soil at S2 and SW30 were lower than in the cover soil at S4. The higher concentrations in the cover soil mix at S4 were similar to values for the interface and into the overburden at SW30 and S2. Concentrations of soluble Mg and K at S4 were typically at or above 150 and 20 $\mu g\ g^{-1}$, respectively. Soluble K concentrations above 20 $\mu g\ g^{-1}$ were observed in the overburden for seven profiles at SW30 and five at S2 (data not shown).

Within the cover soil, all soluble cation concentrations were highest for the S4 site. Concentrations for some of the cations in the interface and overburden material at

Table 3.1. Mean pH and soluble cations (averaged across all slope positions) at SW30 determined from 1:2 soil suspensions and extracts, respectively (± 1 SD).

Depth	pH	Ca	Mg	Na	K
cm		-------------------------------	$\mu g \cdot g^{-1}$	-------------------------------	
0-15	6.6 ± 0.5	47 ± 9	13 ± 4	21 ± 7	3 ± 1
15-30	7.1 ± 0.6	39 ± 20	9 ± 5	22 ± 6	2 ± 1
30-45	7.2 ± 0.5	34 ± 9	8 ± 3	22 ± 7	2 ± 1
45-60	7.4 ± 0.3	34 ± 6	8 ± 2	22 ± 8	2 ± 0
60-75	7.4 ± 0.1	29 ± 7	7 ± 2	24 ± 10	2 ± 1
75-90	7.4 ± 0.2	39 ± 20	9 ± 5	45 ± 31	2 ± 1
90-105	7.5 ± 0.2	54 ± 47	14 ± 17	105 ± 117	3 ± 2
105-120	7.4 ± 0.2	113 ± 136	37 ± 54	174 ± 202	8 ± 13
120-135†	7.3 ± 0.3	162 ± 172	50 ± 55	279 ± 183	13 ± 12
135-150	7.4 ± 0.3	145 ± 131	59 ± 83	446 ± 424	17 ± 20
150-165	7.5 ± 0.3	189 ± 136	66 ± 40	744 ± 386	26 ± 16
165-180‡	7.5	132	60	1000	38

† This depth increment indicates the approximate mean cover thickness (125 cm ± 22 cm); values below this are considered to be OB.

‡ At this depth there was only one sample.

Table 3.2. Mean pH and soluble cations (averaged across all slope positions) at S2 determined from 1:2 soil suspensions and extracts, respectively (± 1 SD).

Depth	pH	Ca	Mg	Na	K
cm		-------------------------------	$\mu g \cdot g^{-1}$	-------------------------------	
0-15	7.1 ± 0.2	41 ± 7	10 ± 3	8 ± 2	8.8 ± 10.3
15-30	7.3 ± 0.3	57 ± 49	13 ± 10	16 ± 14	4.0 ± 3.2
30-45	7.3 ± 0.3	149 ± 167	32 ± 34	34 ± 33	4.9 ± 4.0
45-60	7.2 ± 0.4	149 ± 133	35 ± 28	55 ± 56	5.8 ± 4.9
60-75	7.0 ± 0.3	294 ± 203	82 ± 69	100 ± 129	11.8 ± 12.0
75-90†	7.0 ± 0.4	260 ± 197	94 ± 77	117 ± 153	14.4 ± 13.2
90-105	6.9 ± 0.3	206 ± 165	60 ± 42	39 ± 36	7.9 ± 6.5
105-120	6.4 ± 0.5	188 ± 234	48 ± 56	29 ± 19	4.9 ± 3.1
120-135‡	6.1	36	13	6	3.9

† This depth increment indicates the approximate mean cover thickness (80 cm ± 20 cm); values below this are considered to be OB.

‡ At this depth there was only one sample.

Table 3.3. Mean pH and soluble cations (averaged across all slope positions) at S4 determined from 1:2 soil suspensions and extracts, respectively (± 1 SD).

Depth	pH	Ca	Mg	Na	K
cm		-------------------------------	---------------$\mu g \cdot g^{-1}$	-------------------------------	
0-15	7.0 ± 0.2	232 ± 169	67 ± 44	16 ± 12	25 ± 12
15-30	6.8 ± 0.2	520 ± 64	155 ± 33	42 ± 20	16 ± 4
30-45	6.8 ± 0.3	537 ± 37	192 ± 46	78 ± 34	19 ± 5
45-60	7.0 ± 0.1	524 ± 30	201 ± 47	94 ± 43	20 ± 6
60-75	6.9 ± 0.3	521 ± 25	201 ± 52	94 ± 20	21 ± 7
75-90	6.9 ± 0.4	530 ± 29	228 ± 84	118 ± 29	23 ± 10
90-105	7.1 ± 0.2	523 ± 31	206 ± 69	123 ± 30	23 ± 8
105-120	7.0 ± 0.3	535 ± 36	189 ± 44	126 ± 22	23 ± 7
120-135	7.0 ± 0.2	494 ± 55	159 ± 36	118 ± 25	32 ± 21
135-150	6.9 ± 0.3	416 ± 147	139 ± 61	119 ± 33	24 ± 4
150-165†	6.8 ± 0.3	404 ± 173	144 ± 76	115 ± 36	25 ± 6
165-180	7.0 ± 0.1	384 ± 157	104 ± 44	104 ± 40	22 ± 4
180-195‡	7.1	441	74	52	13
195-210	7.2	327	39	25	5

† This depth increment indicates the approximate mean cover thickness (150 cm ± 26 cm); values below this are considered to be OB.

‡ At and below this depth there was only one sample.

the other two sites, at times, reached levels measured for the S4 cover material. Sodium content was greatest in the SSOB at SW30, exceeding levels at all other sites (Table 3.1). At 150-165 cm depth, the mean Na content was 744 ± 386 μg g^{-1}.

3.3.2 Vegetation

The dominant understory vegetation species at all sites were clover (*Melilotus officinalis* (L.) Lam. and *M. alba Medikus)*, grasses (various), bird's-foot trefoil (*Lotus corniculatus* L.), sow thistle (*Sonchas oleraceous* L.), and dandelion (*Taraxacum offininale* G.H. Weber ex Wiggers) (Table 3.4). These species occurred at all sites, although their proportion of the groundcover varied between sites and within sites. Other species that occurred in sufficient quantities to approximate ground cover proportions are listed in Table 3.4. Percentage of bare ground was greatest, on average, at S2 (13%), followed by S4 (8%), and SW30 (7%) (data shown in Appendix E).

SW30 had the fewest number of trees within a 2 m radius of the sample locations while both S2 and S4 had similar numbers (Table 3.5). At S2, certain sample points were invaded by willows, resulting in a site average of > 3 willow stems within a 2 m radius of the root cores. The large standard deviations in willow numbers were in response to the range of values, from 0 to 9 stems per sample location (data not shown). The two other volunteer tree species recorded were tA and balsam poplar (*Populus balsamifera* L.; bP), although no bP were found at the youngest site (SW30). Within a 2 m radius, SW30, S2, and S4 averaged about 2, 6, and 5 trees, respectively. Half as many trees were within a 2 m radius of root core samples from SW30 compared to S2 and S4.

3.3.3 Roots

3.3.3.1 Root distributions

For all three mixedwood sites, the majority of roots (>70%) occurred in the upper 30 cm of the soil profile (Figure 3.4). The youngest site (SW30) had the lowest mean root density (0.96 cm cm^{-3}) in the upper 30 cm soil depth, S2 had a higher mean root density at 5.41 cm cm^{-3}, while the oldest site studied (S4) had a mean root density eight times that of SW30 at 7.99 cm cm^{-3}.

Root length density for each site declined sharply below the 30 cm soil depth (Figure 3.4). More roots (>4 and >10 times at S2 and S4, respectively) were found at

Table 3.4. Understory plant species identified at each reclaimed study site.

Location	Species Identified†
Common to all sites	clover (*Melilotus officinalis* (L.) Lam. and *M. alba Medikus)* dandelion (*Taraxacum offininale* G.H. Weber ex Wiggers) sow thistle (*Sonchas oleraceous* L.) bird's-foot trefoil (*Lotus corniculatus* L.) horsetail (*Equisetum* L.) grasses (various)
SW30	fireweed (*Chamerion angustifolium* (L.) Holub) Canada thistle (*Cirsium arvense* (L.) Scop.) pea vine (*Lathyrus* L.) raspberry (*Rubus idaeus* L.)
S2 South	fireweed (*Chamerion angustifolium* (L.) Holub) raspberry (*Rubus idaeus* L.) milkvetch (*Astragalus* L.)
S4	strawberry (*Fragaria* L.)

† Plant species names are listed in agreement with the Integrated Taxonomic Information System (ITIS, 2008).

Table 3.5. Mean number of volunteer and planted tree species within a 2 m radius of root core sample locations (± 1 SD; n = 11, unless otherwise noted).

	Planted		Volunteer			Total
Site	**tA†**	**wS**	**tA**	**bP**	**wi**	**all spp**
SW30‡	0.9 ± 0.8	0.7 ± 1.0	0.4 ± 0.7		0.4 ± 0.9	2.4 ± 1.6
S2	0.9 ± 0.7	0.8 ± 0.8	0.8 ± 1.6	0.4 ± 0.8	3.3 ± 3.6	6.2 ± 3.5
S4	1.3 ± 0.9	1.3 ± 0.8	0.9 ± 1.2	0.6 ± 1.0	0.9 ± 2.6	5.0 ± 3.0

† tA, trembling aspen; wS, white spruce; bP, balsam poplar; wi, willow.
‡ At SW30, n= 10.

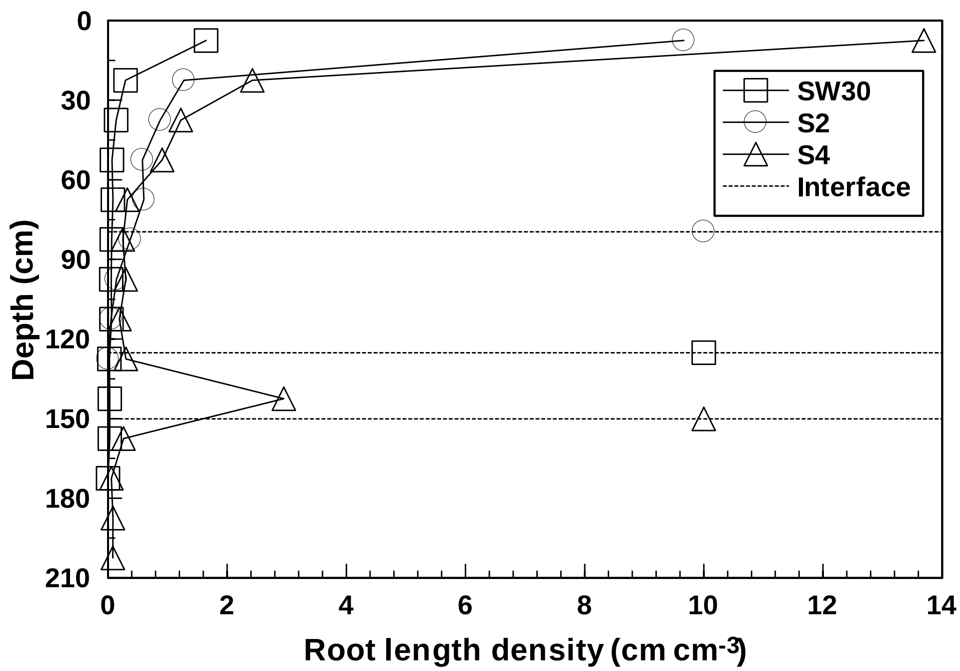


Figure 3.4. Mean root length density distribution with soil depth for each site (n=12). Dashed lines with open legend symbols indicate mean cover thickness (interface location) for each site.

greater depth in the profile at the older sites compared to SW30. The increase in root density at 135-150 cm depth for S4 coincided with a peat sample in which the roots proliferated.

Regardless of stand age, thickness of the soil cover, or soil properties, roots were observed in the overburden material. The proportion of root length found in the OB averaged between 1.3 and 2.2% of the total root length at each site.

3.3.3.2 Proportion of roots in different diameter classes

At all sites and for all soil depths, greater than 95% of the root length was <1 mm in diameter (Table 3.6). This diameter class also accounted for 99% of the root length in the 0-15 cm depth increment (data not shown), and greater than 98% when all depths were considered. Roots 1-2 mm in diameter represented between 0.7 and 1.4% of the total root length for the three sites, while roots 2-5 mm in diameter comprised 0.2% of the total root length at only S2 and S4. In terms of root weight, the <1 mm diameter class accounted for more than 50% of the weight from all roots in profiles at S2 and S4, and more than 65% for SW30 (Table 3.6). In the 0-15 cm depth increment, the <1 mm diameter class made up 67.4, 55.5 and 60.0 % of the total root weight found in the profiles for SW30, S2, and S4, respectively (data not shown). Although the larger root diameter classes (>1 mm) accounted for only a small proportion of the total root length, they represented a larger proportion of the total root weight. For example, at S4, although the 1-2 mm diameter class only accounted for 0.7% of the total root length, it represented 13.9% of the total roots by weight.

3.3.4 Root-Soil-Slope Interactions

Root length densities at SW30 (0-15 cm depth) for the upper slope (2.41 ± 1.18 cm cm^{-3}) and mid-slope 1 (2.79 ± 3.05 cm cm^{-3}) positions were more than double those of the lower slope (1.02 ± 0.03 cm cm^{-3}) and about seven times greater than mid-slope 2 (0.36 ± 0.10 cm cm^{-3}) (Figure 3.5). Electrical conductivity in the soil cover for all four slope positions ranged from 0.60 to 6.32 dS m^{-1} and had similar trends with soil depth, generally increasing towards the cover/OB interface. In the OB, however, EC values were higher than the cover soil and EC for the upper slope (9.30 ± 0.90 dS m^{-1}) and mid-slope 1 (8.54 ± 1.39 dS m^{-1}) were twice that for the mid-slope 2 (4.66 ± 1.96 dS m^{-1}) and

Table 3.6. Percent of total roots in each diameter class from each site.

	Total root length			Total root dry weight		
Diameter Class	**SW30**	**S2 South**	**S4**	**SW30**	**S2 South**	**S4**
mm	------------------------------------			% ------------------------------------		
<1	98.9	98.4	99.0	66.5	54.5	52.8
1-2	1.1	1.4	0.7	33.5	22.6	13.9
2-5	0.0	0.2	0.2	0.0	18.8	31.9
>5	0.0	0.0	0.0	0.0	4.1	1.5

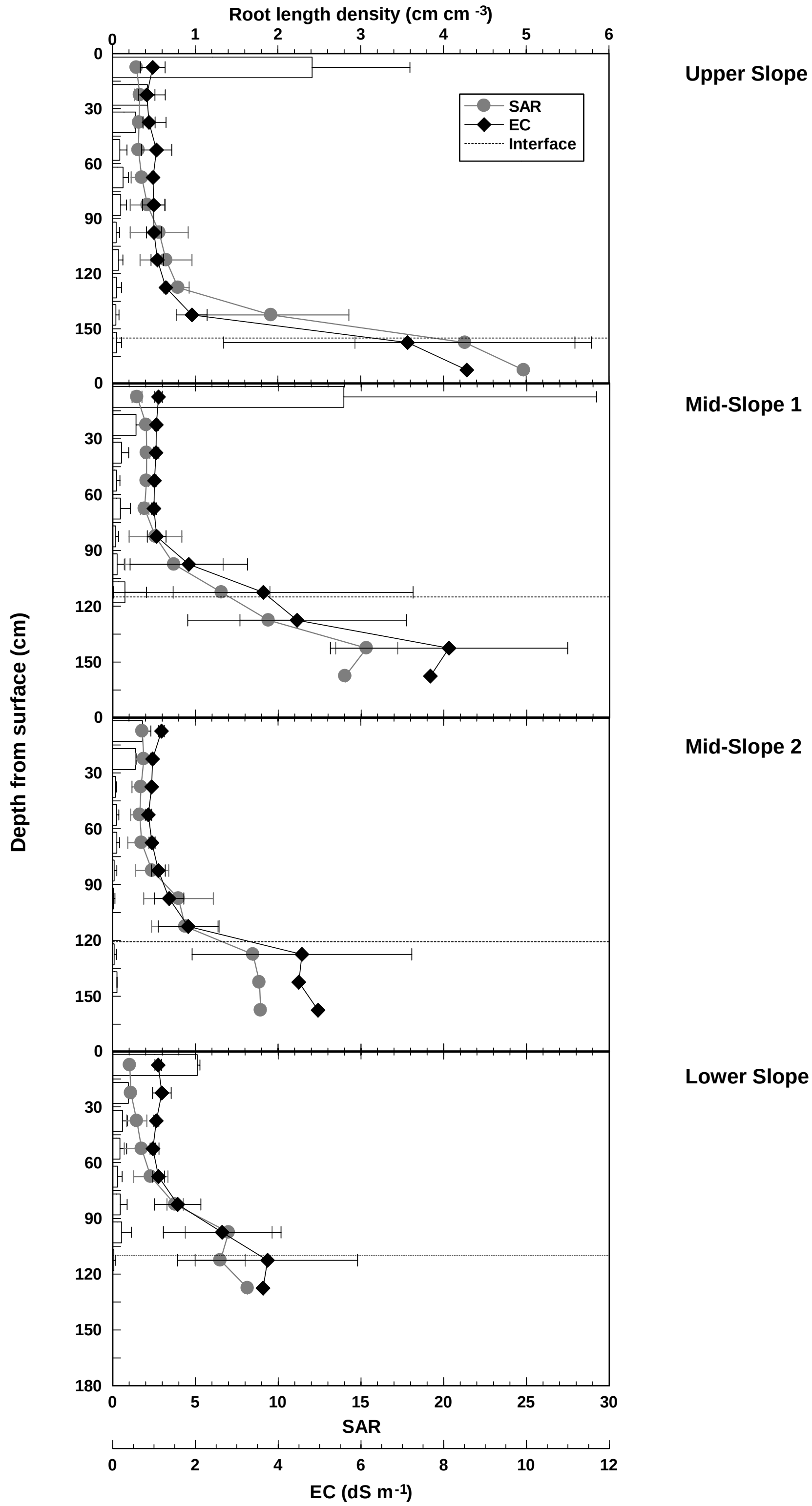


Figure 3.5. Mean root length density, EC, and SAR profiles for each slope position at SW30. Root length density is denoted by the horizontal bars. Error bars represent ± 1 SD. The horizontal dashed line represents the average depth of the cover/OB interface.

lower slope (4.50 ± 1.03 dS m^{-1}) positions. Generally, EC values in the OB were below 12 dS m^{-1} and less than 4 dS m^{-1} in the majority of the cover soil. The SAR followed similar trends to that of EC throughout the soil profile with SAR values being highest in the OB for the upper slope (24.77 ± 2.97) and mid-slope 1 (13.54 ± 3.39) positions. Values for SAR were below 15 and 30 in the cover soil and OB, respectively. Of the three sites, slope differences were most apparent at SW30 (Figure 3.5) where the highest concentration of salts and sodium appeared in samples from the upper slope (maximum SAR 27.7 and EC 10.3 dS m^{-1}) and decreased down slope. Values for SAR and EC at the lower slope reached maximums less than half that of the upper slope and ranged from 1.01 to 10.04 and 0.90 to 5.63 dS m^{-1}, respectively.

For S2, highest root length densities for the 0-15 cm soil depth were found in the mid-slope 1 position (17.32 ± 18.06 cm cm^{-3}) and lowest densities in the mid-slope 2 position (3.50 ± 0.65 cm cm^{-3}) (Figure 3.6). The upper and lower slope positions had similar rooting distributions in the soil profile with root length densities (in the upper 15 cm) of 9.97 ± 3.35 and 7.87 ± 1.57 cm cm^{-3}, respectively. Mean EC values were higher in the upper slope (maximum 7.60 dS m^{-1}), mid-slope 2, and lower slope positions, compared to the mid-slope 1 position for both the cover soil and OB. Measured EC values were below 5 and 8 dS m^{-1} in the cover soil and OB, respectively. The upper slope had much higher SAR values throughout the soil profile compared to the other slope positions, with highest values (maximum 8.21) in the OB. The other three slope positions did not see a large increase in SAR in the OB. The SAR was determined to be < 6 and < 9 in the cover and OB, respectively. The maximum SAR and EC determined for mid-slope 1, mid-slope 2, and the lower slope were similar to each other (SAR 2.11, 2.02, 2.44; EC 4.81, 4.74, 4.94 dS m^{-1}, respectively). Diffusion of salts and sodium upward from the SSOB into the cover soil was evident at SW30 (Figure 3.5; Appendix D) and at S2 (Figure 3.6; Appendix D) by the increased EC and SAR values above the interface.

At the oldest site, S4, the highest root length density occurred in the lower slope position (18.18 ± 14.35 cm cm^{-3}) compared to the other three slope positions (Figure 3.7). Mean root length densities in the 0-15 cm soil depth were 12.12 ± 8.41, 10.67 ± 4.49, and 13.80 ± 2.52 cm cm^{-3} for the upper slope and mid-slopes 1 and 2, respectively. Root

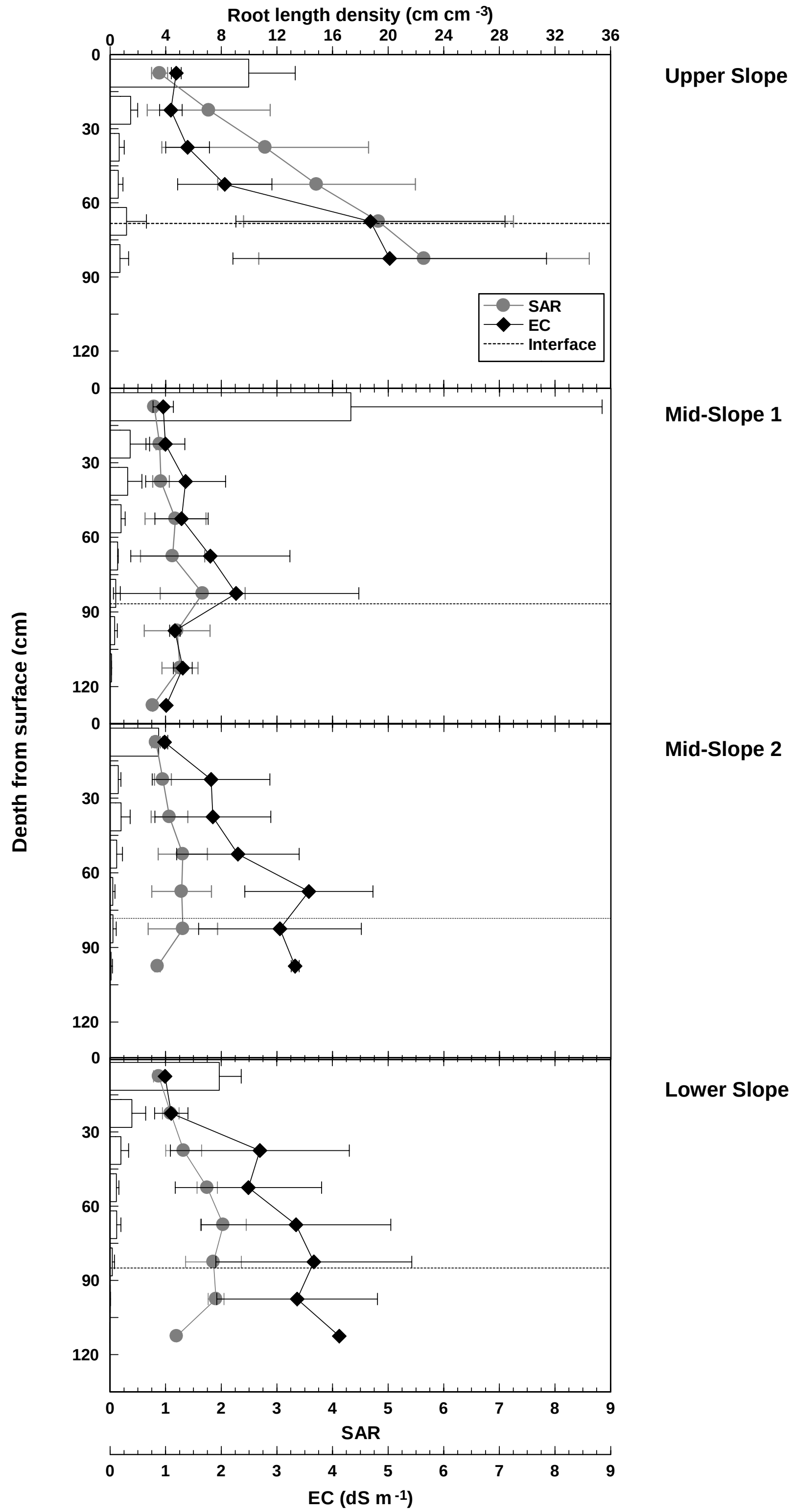


Figure 3.6. Mean root length density, EC, and SAR profiles for each slope position at S2. Root length density is denoted by the horizontal bars. Error bars represent ± 1 SD. The horizontal dashed line represents the average depth of the cover/OB interface.

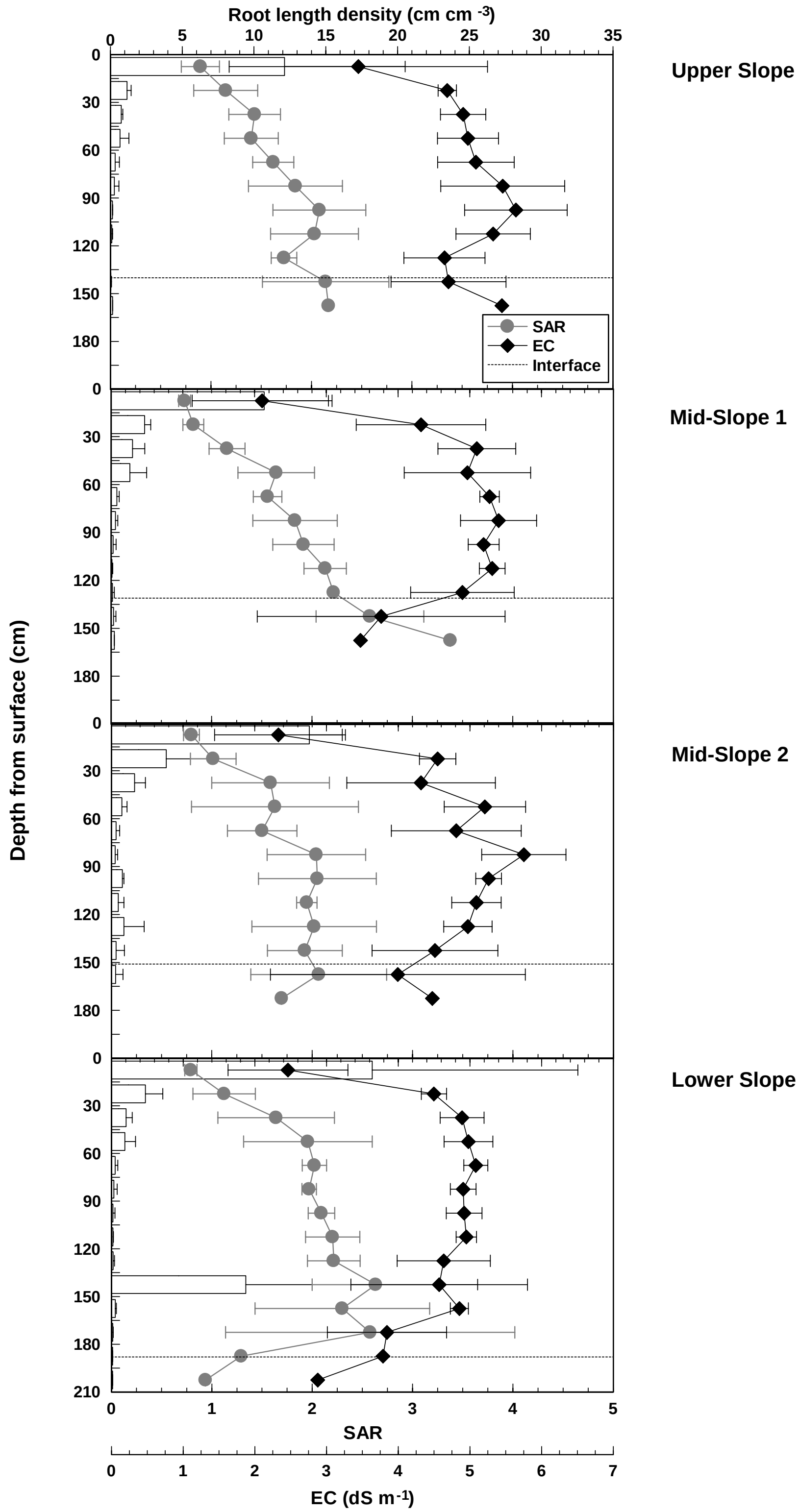


Figure 3.7. Mean root length density, EC, and SAR profiles for each slope position at S4. Root length density is denoted by the horizontal bars. Error bars represent ± 1 SD. The horizontal dashed line represents the average depth of the cover/OB interface.

length densities decreased rapidly after the 0-15 cm soil depth; however, an increase in root length was found at the 135-150 cm depth in the lower slope. The SAR and EC values measured from the samples at S4 were similar between the OB and cover. Electrical conductivity values for all slope positions were lower in the surface 15 cm (1.39 to 4.68 dS m^{-1}) and about 4.5 to 6.0 dS m^{-1} throughout the rest of the soil profile. In the OB, EC was generally lower compared to the cover soil. The SAR showed similar trends throughout the soil profile and ranged between 0.68 and 2.97. Values for SAR were below 3 in the cover and 4 in the OB. At SW30 and S2, the majority of the samples from the cover soil had low EC values (below 1.5 dS m^{-1}) while at S4, the majority was between 4 and 6 dS m^{-1}. Values determined for SAR at S4 were similar to the majority of values measured at S2 and slope differences were minor.

Correlations for RLD_u (root length density calculated for the upper 30 cm of the soil profile) were performed on transformed data as outlined in Section 3.2.4. When all sites were analyzed together, a small positive correlation was found with the number of trees within a 2 m radius and RLD_u, r = .41, $p < .05$ (Table 3.7). The greater the number of trees within 2 m of the root core sample location, the higher the RLD_u of that reclaimed soil profile. When sites were interpreted separately, percent cover was negatively correlated with RLD_u, r = -.70, $p < .05$ and positively with movement down slope, r = .74, $p < .01$, at SW30 (Table 3.8). As such, the understory cover was greater at lower slope positions while RLD_u was reduced for those profiles. The correlation coefficient between slope and RLD_u was negative, r = -.57, $p > .05$, but it was not a significant indication of an increase in RLD_u with movement upslope. At S2, RLD_u was not correlated with the site variables examined, but a positive relationship existed between percent cover and the number of trees within a 2 m radius of the core, r = .63, $p < .05$ (Table 3.9). This relationship meant there was increased understory cover with an increasing number of trees near the sample location. There was a strong correlation between RLD_u and the number of trees within a 2 m radius at S4, r = .70, $p < .05$ (Table 3.10). The greater the number of trees near the sample location at this site, the greater the RLD_u for the profile.

Correlation analyses for RLD with soil properties from individual samples (slope included) were performed using transformed data (refer to Section 3.2.4) on a site-by-site

Table 3.7. Pearson's correlation coefficients (r) for properties across all of the reclaimed sites (n = 36).

	Correlation coefficients (r)			
Variables	**RLD_u†**	**Slope‡**	**Cover§**	**Trees¶**
RLD_u	1.00			
Slope	-.10	1.00		
Cover	-.15	-.04	1.00	
Trees	.45*	-.02	.28	1.00

* Significant at $p < .05$

† RLD_u, root length density, calculated for the upper 30 cm of the profile ($cm\ cm^{-3}$)

‡ Slope, numbered from 1 at the upper slope to 4 at the lower slope; increase in slope numbering means a movement down slope

§ Cover, percentage of ground covered by understory vegetation at each sampling location (%)

¶ Trees, number of trees within a 2 m radius of each sampling location

Table 3.8. Pearson's correlation coefficients (r) for root length density and site properties at SW30 (n = 12).

	Correlation coefficients (r)			
Variables	**RLD_u†**	**Slope‡**	**Cover§**	**Trees¶**
RLD_u	1.00			
Slope	-.57	1.00		
Cover	-.73**	.74**	1.00	
Trees	-.32	-.12	.00	1.00

** Significant at $p < .01$

† RLD_u, root length density, calculated for the upper 30 cm of the profile ($cm\ cm^{-3}$)

‡ Slope, numbered from 1 at the upper slope to 4 at the lower slope; increase in slope numbering means a movement down slope

§ Cover, percentage of ground covered by understory vegetation at each sampling location (%)

¶ Trees, number of trees within a 2 m radius of each sampling location

Table 3.9. Pearson's correlation coefficients (r) for root length density and site properties at S2 (n = 12).

Variables	Correlation coefficients (r)			
	RLD_u†	**Slope‡**	**Cover§**	**Trees¶**
RLD_u	1.00			
Slope	-.33	1.00		
Cover	.04	-.31	1.00	
Trees	-.11	-.12	.63*	1.00

* Significant at $p < .05$

† RLD_u, root length density, calculated for the upper 30 cm of the profile (cm cm^{-3})

‡ Slope, numbered from 1 at the upper slope to 4 at the lower slope; increase in slope numbering means a movement down slope

§ Cover, percentage of ground covered by understory vegetation at each sampling location (%)

¶ Trees, number of trees within a 2 m radius of each sampling location

Table 3.10. Pearson's correlation coefficients (r) for root length density and site properties at S4 (n = 12).

Variables	Correlation coefficients (r)			
	RLD_u†	**Slope‡**	**Cover§**	**Trees¶**
RLD_u	1.00			
Slope	.39	1.00		
Cover	.35	-.23	1.00	
Trees	.69*	.20	.46	1.00

* Significant at $p < .05$

† RLD_u, root length density, calculated for the upper 30 cm of the profile (cm cm^{-3})

‡ Slope, numbered from 1 at the upper slope to 4 at the lower slope; increase in slope numbering means a movement down slope

§ Cover, percentage of ground covered by understory vegetation at each sampling location (%)

¶ Trees, number of trees within a 2 m radius of each sampling location basis. Of the variables that were highly correlated with RLD, soil depth showed the strongest relationship, indicative of decreasing RLD with increasing depth in the soil at all sites (r = -.77, -.68, and -.70 at SW30, S2, and S4, respectively, $p < .001$; Table 3.11 to 3.13). Root length density was also negatively correlated with Na and EC at all sites. Higher RLDs were observed where the soil contained less soluble Na and salts.

At SW30, RLD was negatively related to Ca, Mg, and Na, but positively related to pH and movement upslope (Table 3.11). Therefore, RLD was greater where the soluble Ca, Mg, and Na content of the soil was lower, the pH was higher, and increased with movement upslope. At S2, RLD was negatively related to pH, Na, EC, and SAR (Table 3.12), while at S4, the negative relationships with RLD included Na, EC, and SAR (Table 3.13).

Controlling for depth, a partial correlation matrix was developed for each site to further examine the relationships of the remaining soil properties with RLD. Significant correlations shifted and variables such as SAR had small correlation coefficients with no effect on RLD (r = .25, .23, -.21, $p < .05$ for SW30, S2, and S4, respectively). At SW30 (Table 3.11), slope had a small influence on the RLD (r = -.30, $p < .01$), while at S2 (Table 3.12), several variables (pH negatively; Ca, Mg, K, and EC positively) showed some correlation with RLD, but there were no strong relationships. At S4 where soil properties varied less with depth (Figure 3.7) than at the other two sites, there were no clear relationships for any variables (Ca, Mg, Na, SAR, EC; r = -.22, -.24, -.23, -.21, and -.28, $p < .05$) with RLD (Table 3.13).

Some of the soil variables shared such a close linear relationship, that multicollinearity was likely. The block of variables highly correlated with each other included Ca, Mg, Na, K, EC, and SAR (or the logarithmic transformations of the variables noted in Section 3.2.4). At SW30, the variable combinations that were not significantly correlated at $p < .001$ were Ca and SAR (r = .19, $p < .1$) and Mg and SAR (r = .33, $p < .01$) (Table 3.11). At S2, all variables in this block were significantly correlated ($p < .001$) (Table 3.12). At S4, the block of soil variables were not as closely related, but multicollinearity could exist between EC and Mg, EC and Ca, and Na and SAR (all r = .88, $p < .001$) (Table 3.13).

Table 3.11. Pearson's correlation coefficients (r) and first order partial correlation matrices of root length density, slope and chemical soil characteristics for SW30.

					Correlation coefficients (r)					
Variables	**RLD†**	**Slope‡**	**pH§**	**Ca¶**	**Mg**	**Na**	**K**	**EC#**	**SAR††**	**Depth‡‡**
RLD	1.00									
Slope	-.23*	1.00								
pH	.30**	-.14	1.00							
Ca	-.45***	.28*	-.01	1.00						
Mg	-.46***	.15	-.04	.97***	1.00					
Na	-.30**	-.04	.16	.70***	.78***	1.00				
K	-.12	-.18	.21	.67***	.71***	.45***	1.00			
EC	-.44***	.14	.00	.95***	.98***	.83***	.68***	1.00		
SAR	-.09	-.27*	.27*	.30**	.43***	.89***	.21	.51***	1.00	
Depth	-.77***	.05	-.44***	.43***	.50***	.45***	.13	.48***	.31**	1.00
					Partial correlation coefficients (controlling for depth)					
RLD	1.00									
Slope	-.30**	1.00								
pH	-.08	-.14	1.00							
Ca	-.20	.28**	.22	1.00						
Mg	-.13	.15	.24*	.96***	1.00					
Na	.09	-.07	.45***	.62***	.72***	1.00				
K	-.04	-.18	.29**	.69***	.76***	.45***	1.00			
EC	-.11	.14	.28*	.94***	.98***	.79***	.72***	1.00		
SAR	.25*	-.30**	.47***	.19	.33**	.88***	.19	.44***	1.00	

* Significant at $p < .05$

** Significant at $p < .01$ level

*** Significant at $p < .001$ level

† RLD, root length density calculated for the each sampling depth within the profile (cm cm^{-3})

‡ Slope, numbered from 1 at the upper slope to 4 at the lower slope; an increase in slope means a movement down slope

§ pH, pH value determined from 1:2 dilution method

¶ Soluble Ca, Mg, Na, and K (mg L^{-1})

\# EC, electrical conductivity (dS m^{-1})

†† SAR, sodium absorption ratio ((mmolc $L^{-1})^{-1/2}$)

‡‡ Depth, average depth for each 15 cm increment into the soil (cm)

Table 3.12. Pearson's correlation coefficients (r) and first order partial correlation matrices of root length density, slope and chemical soil characteristics for S2.

					Correlation coefficients (r)					
Variables	**RLD†**	**Slope‡**	**pH§**	**Ca¶**	**Mg**	**Na**	**K**	**EC#**	**SAR††**	**Depth‡‡**
RLD	1.00									
Slope	-.06	1.00								
pH	-.53***	-.06	1.00							
Ca	-.09	.12	-.31**	1.00						
Mg	-.05	.11	-.36***	.98***	1.00					
Na	-.41***	-.05	.15	.76***	.74***	1.00				
K	-.14	-.05	-.12	.86***	.86***	.81***	1.00			
EC	-.31**	.04	.04	.88***	.87***	.94***	.89***	1.00		
SAR	-.48***	-.11	.30**	.59***	.57***	.97***	.70***	.86***	1.00	
Depth	-.68***	-.17	.45***	.44***	.41***	.79***	.53***	.69***	.83***	1.00
					Partial correlation coefficients (controlling for depth)					
RLD	1.00									
Slope	-.25**	1.00								
pH	-.35***	.01	1.00							
Ca	.31**	.22*	-.63***	1.00						
Mg	.35***	.20*	-.67***	.98***	1.00					
Na	.29**	.13	-.38***	.76***	.75***	1.00				
K	.35***	.05	-.47***	.83***	.83***	.76***	1.00			
EC	.30**	.22*	-.41***	.89***	.90***	.89***	.85***	1.00		
SAR	.23*	.05	-.14	.44***	.45***	.92***	.56***	.70***	1.00	

* Significant at $p < .05$
** Significant at $p < .01$ level
*** Significant at $p < .001$ level
† RLD, root length density calculated for the each sampling depth within the profile (cm cm^{-3})
‡ Slope, numbered from 1 at the upper slope to 4 at the lower slope; an increase in slope means a movement down slope
§ pH, pH value determined from 1:2 dilution method
¶ Soluble Ca, Mg, Na, and K (mg L^{-1})
\# EC, electrical conductivity (dS m^{-1})
†† SAR, sodium absorption ratio ((mmolc $L^{-1})^{-1/2}$)
‡‡ Depth, average depth for each 15 cm increment into the soil (cm)

Table 3.13. Pearson's correlation coefficients (r) and first order partial correlation matrices of root length density, slope and chemical soil characteristics for S4.

					Correlation coefficients (r)					
Variables	**RLD†**	**Slope‡**	**pH§**	**Ca¶**	**Mg**	**Na**	**K**	**EC#**	**SAR††**	**Depth‡‡**
RLD	1.00									
Slope	-.02	1.00								
pH	-.04	.06	1.00							
Ca	-.20*	-.03	-.12	1.00						
Mg	-.18*	-.26**	-.29**	.68***	1.00					
Na	-.54***	.12	-.03	.34***	.47***	1.00				
K	-.08	-.08	.01	-.05	.17	.24**	1.00			
EC	-.34***	-.12	-.20*	.87***	.87***	.60***	.13	1.00		
SAR	-.57***	.16	.03	.06	.18*	.92***	.22*	.32***	1.00	
Depth	-.70***	.16	.09	.06	.02	.58***	.14	.20*	.66***	1.00
					Partial correlation coefficients (controlling for depth)					
RLD	1.00									
Slope	.13	1.00								
pH	.03	.05	1.00							
Ca	-.22*	-.04	-.12	1.00						
Mg	-.24**	-.26**	-.29**	.68***	1.00					
Na	-.23**	.03	-.10	.37***	.56***	1.00				
K	.03	-.11	.00	-.06	.16	.20*	1.00			
EC	-.28**	-.16	-.22*	.88***	.88***	.61***	.11	1.00		
SAR	-.21*	.08	-.03	.02	.22*	.88***	.17	.26**	1.00	

* Significant at $p < .05$
** Significant at $p < .01$ level
*** Significant at $p < .001$ level
† RLD, root length density calculated for the each sampling depth within the profile (cm cm^{-3})
‡ Slope, numbered from 1 at the upper slope to 4 at the lower slope; an increase in slope means a movement down slope
§ pH, pH value determined from 1:2 dilution method
¶ Soluble Ca, Mg, Na, and K (mg L^{-1})
\# EC, electrical conductivity (dS m^{-1})
†† SAR, sodium absorption ratio ((mmolc $L^{-1})^{-1/2}$)
‡‡ Depth, average depth for each 15 cm increment into the soil (cm)

3.4 Discussion

3.4.1 Soil

Reconstructed soils tend to have higher bulk densities or greater compaction than natural sites (McSweeney and Jansen, 1984). Density values calculated for SW30 and S2 followed this trend, averaging above 1.5 g cm^{-3} and as high as 1.9 g cm^{-3}. Bulk densities above 1.46 g cm^{-3} for clay loams and 1.75 g cm^{-3} for sand textures have been reported to restrict or limit root growth (Russell, 1977; Daddow and Warrington, 1983). Within the Fort McMurray Alberta oil sand mine region, Yarmuch et al. (2002) reported no difference in soil structure quality between undisturbed and disturbed soils based on bulk density and hydraulic conductivity measurements. Bulk density for reclaimed sites averaged between 1.60 and 1.65 g cm^{-3} in the upper subsoil and between 1.64 and 1.78 g cm^{-3} in the lower subsoil, and although compared to values for undisturbed sites, the relationship to root growth was not examined. Heavy equipment compaction pans with bulk densities greater than 1.7 g cm^{-3} represented the lower limit for rooting of eastern white pine on reclaimed mine profiles in West Virginia (Andrews et al., 1998). These growth limiting bulk density values (Russell, 1977; Daddow and Warrington, 1983; Andrews et al., 1998) were all within the range determined in this study; however, with the higher clay content of the soil covers in this study and the high soil penetrometer measurements obtained, it suggests that there could be potential for reduced root penetration in these covers.

The EC and SAR increased with depth at SW30 and S2, especially directly above the interface from the SSOB as a result of salts and Na diffusing upward into the cover soil from the SSOB (Kessler, 2007). At these sites, the higher concentrations of salts were deeper in the profile, suggesting that there would be little effect on root densities at the soil surface. However, it is interesting to note that there was a landscape position effect at the S2 site where the upper slope had higher salt levels that could adversely affect vegetation growth at this slope position. In naturally saline landscapes examined in Alberta, Purdy et al. (2005) found that soils with high salinity (>10 dS m^{-1}) only at depth (80-100 cm), showed little difference in boreal species composition from non-saline forest habitats. At S4, higher salinity and sodicity levels were observed throughout the cover soil suggesting that the material used in the soil mix may present some concerns for root growth due to the high salt levels. Some tree species are susceptible to salinity at EC levels >4 dS m^{-1}, with deciduous species more tolerant than coniferous species (Howat, 2000). Shoot growth is generally more responsive to increasing EC than root growth (Bernstein and Kafkafi, 2002; Chen et al., 2002; Fung et al., 1998). Andrews et al. (1998) found that heights of white pine in Virginia decreased with increasing EC on reclaimed minesoils, while McFee et al. (1981) reported three different overburden materials with EC levels (2.1 to 8.4 mmho cm^{-1} = dS m^{-1}) which reduced plant growth for studies in Indiana. Staples and Van Rees (2001) reported that white spruce were susceptible to salinity stress at EC levels > 0.10 dS m^{-1} when ash was applied to the soil and Maynard et al. (1997) reported that white spruce had a 50% reduction in height growth when exposed to an EC of 0.5 dS m^{-1} compared to the control. Renault et al. (1998; 1999) noted injury in wS and tA to low salt concentrations compared to dogwood. Tamarack had moderate tolerance to salinity when tested with 30 and 60 mmol L^{-1} NaCl with only the shoots significantly affected at low salinity and the roots showing more signs of injury at the higher salt concentration (Renault, 2005). The observations by Purdy et al. (2005) and the current EC and SAR levels in the reconstructed soils in our study suggests that sites with deeper salinity (> 80 cm) could develop forest ecosystems in a similar manner to the naturally saline forest-zones in Alberta provided that salt migration into the cover does not occur to any great extent. The slightly saline nature of the cover soil at S4 may impact or may have already impacted the forest growth; however, numerous other factors, such as plant sensitivity, genetic variability, duration of stress, concentration and type of salts, and environmental variables need to be considered when determining salt effects on vegetation (Bernstein and Kafkafi, 2002).

3.4.2 Roots

At all sites and soil depths, greater than 95% of the root length was <1 mm in diameter. These fine roots dominated the soil profile in terms of length. This is similar to findings by Parker and Van Lear (1996) where 90% of loblolly pine roots (South Carolina) were <4 mm. Fine roots (<2 mm) in a Saskatchewan boreal forest accounted for 94 to 100% of the total root length for five species examined (Van Rees, 1997). Likewise in Alberta, Strong and La Roi (1983b) found that 50% of all roots were within the upper 7 to 19 cm of the rooting zone, coarse roots (>5 mm) were usually limited to the upper 10 cm, and although fine roots existed throughout the profile, they were most numerous in the upper 10 cm as well. It is uncertain, however, if salinity affects all different diameter root classes similarly, in terms of function and growth, and thus, warrants further study.

Root densities at each site were high in the surface soil of the reconstructed soil profiles and decreased with depth, showing a typical boreal forest root distribution pattern (Strong and La Roi, 1983b; Van Rees, 1997) despite stand age. In a summary paper by Jackson et al. (1996), boreal forest biomes had some of the shallowest rooting profiles with 80-90% of the roots in the upper 30 cm of the soil, while temperate conifer forests had one of the deepest profiles with only 50% of their roots in the top 30 cm of soil. Strong and La Roi (1983b) reported that young aspen stands on both sand and clay loam series in Alberta had more near-surface roots than the older stands (20-80%). However, the youngest stand they studied was 19 years of age and the oldest was 170 years, whereas the oldest site examined in this study was 13 years of age (from planting date). At the SCL reclaimed study sites, root length in the upper 30cm ranged from 52 to 98% of the total roots in profiles and accounted for, on average, 76.6 ± 14.5, 78.8 ± 11.8, 77.3 ± 9.3 % of the total roots in profiles at SW30, S2, and S4, respectively (data not shown). Van Rees (1997) found the average total root length values to increase from 6 and 10 year old mixedwood stands to 20 years of age, and then decrease for older stands. This increase in root length for younger stands was primarily from grasses and species other than the tA and wS. Aspen root density decreased from the 6 and 10 year old stands to its lowest in the 20 year old stand, increasing to 60 years, then falling again in the 110 year old stand, while wS root length generally increased with stand age (Van Rees, 1997). Our data is comparable with other studies (Strong and La Roi, 1983b; Jackson et al., 1996; Van Rees, 1997), although it is uncertain which species were contributing to the root length at the different soil depths and if those amounts and species rooting distributions varied between sites. It also is unknown if the tree roots have explored the reconstructed soil profile to the extent observed by other researchers on natural sites.

Depth of rooting can vary depending on species and soil properties. Strong and La Roi (1983b) found rooting depth increased with stand age on the aspen-sand series, but found no trend for the clay loam series. Van Rees (1997) reported fine roots to 120 cm depth in their mixedwood stands on different soils types. Stone and Kalisz (1991) summarize rooting depths for numerous tree species and reported tA roots to > 3 m depth and wS roots to a 3 m depth. Van Rees (1997) reported up to 60% of the root length density for all species was in the LFH layer for boreal mixedwood stands; however, an average of 10 and 14% of the root length was deeper than 60 cm for wS and tA, respectively. At all reclaimed sites in this study, roots were found at depth and a small proportion of root length (between 1.3 and 2.2%) was found in the OB material (mean depths of OB ranged from 80 to 150 cm) at all sites regardless of stand age, cover thickness, or soil properties. Although roots were found in the OB material, it is not known which species were able to grow in these higher salt conditions. Understory vegetation occupied almost 85% of the ground cover with yellow and white sweet clover being the dominant understory species. Although it is atypical for boreal mixedwood ecosystems, sweet clover is common on the reclaimed areas as it was included in prior reclamation seed mixes and has since spread to other areas. Sweet clover has been noted for its tolerance of moderately saline (4 to 8 dS m^{-1}) conditions (Henry, 2003) and use in agricultural salinity reclamation (Holm, 1983). Other understory species included grasses, sow thistle, bird's-foot trefoil, and volunteer tree species such as willow and balsam poplar which may have attributed to this root length in the OB. Yield reduction of bird's-foot trefoil by 10, 25 and 50 % occurred at EC values around 5.9, 8.1, and 10.0 mS cm^{-1} (Carter, 1975) while Holm and Henry (1982) classified some of the wheat grasses as tolerant to severe saline conditions (8 to 16 mS cm^{-1}). However, without identifying the specific roots when root sampling it is difficult to identify which species is growing in the OB and other methods such as tracers (strontium, rubidium) may be needed to identify these species (Soileau, 1973; Pinkerton and Simpson, 1979; Van Rees and Comerford, 1986; Capo et al., 1998).

3.4.3 Interactions

Cover thickness varied between sites based on the reclamation prescription provided and also within a site showing a trend with slope position. Reverse patterns were seen at SW30 and S4 (cover deepest at the upper and lower slopes, respectively), while a more uniform thickness was achieved at S2. Differences in cover thickness also meant variation in the depth of the rooting zone that was not influenced by the upward migration of salts from the SSOB. Additionally, EC and SAR measured in the soil profiles changed with slope positions; levels at SW30 and S2 were highest in the upper slope positions while S4 was more variable. Less water has moved through the profiles in the upper slope positions versus the lower slopes which could potentially lead to this effect. Root densities varied with slope as well, suggesting the importance of other variables related to slope that were not examined. One such property is soil moisture. Although not measured in their study, Ares and Peinemann (1992) suggested that soil moisture, of all the soil factors, probably plays the largest role in determining root development and distribution, and that variables connected to water availability (such as soil texture) may also affect root densities and distribution. These parameters would be important considerations for any future research at these sites. Salt profiles may differ with landscape position or slope and thus affect vegetation establishment and rooting distributions.

High correlations between the variables Ca, Mg, K, Na, EC, and SAR were anticipated as they contribute to the salt content of the soil, while Ca, Mg, and Na were used to determine SAR values. At SW30 and S2, the OB is saline and sodic in nature creating an inverse relationship to root length density which had greatest concentrations near the surface. At S4, the cover soil was higher in salts, making the relationship more complex. Strong and La Roi (1985) found numerous soil variables to be negatively correlated with root densities including Ca, Mg, clay content, depth, and bulk density. Here, the negative relationships of soluble cations, EC or SAR with RLD at SW30 and S2 may be nested in with the influence of depth in the soil. Strong and La Roi (1985) found depth, Ca, and Mg to be negatively correlated with root densities; however, the influence was indirect, as Ca and Mg were present at depth due to mineralogy and not pedogenic processes.

Depth was strongly correlated with RLD (log-transformed) at each site. This response was also found by Strong and La Roi (1985) for natural stands of jack pine, wS, and tA in Alberta, and by Ares and Peinemann (1992) in temperate coniferous forests of

Argentina, while Sainju and Good (1993) reported an exponential decrease of root density with soil depth. In addition to depth, Na and EC were found to have significant negative relationships with RLD at each reclaimed site, in confirmation of the statement that roots do not grow well with increased salt or sodium (Bernstein and Kafkafi, 2002). Electrical conductivity was found to be negatively associated with tree growth on reclaimed minesoils in Virginia (Andrews et al., 1998), although root growth was not examined.

3.5 Conclusions

Understory vegetation cover at the sites was slightly greater at the younger site than the older site. At the young site, canopy was completely open, whereas in the older stand there was more canopy cover. Volunteer trees were growing at all the sites, indicating that conditions were favorable for growth in these young stands. This suggests the potential for ecosystem functionality and the regeneration of native species.

Soil physical properties such as bulk density and soil resistance values approached threshold values for restricting root growth particularly at S2 and may be a concern for future root growth. Although salinity levels were higher at depth in the profiles at SW30 and S2, they were similar to those found in naturally occurring saline forest-zones. We anticipate, given no further accumulation of or upward migration of salts into the non-saline, non-sodic cover, that these sites will develop forest cover similar to naturally occurring saline forest sites. The slightly saline nature of the cover soil at S4 could impact the forest productivity at this site, however further monitoring of tree growth, health, and soil properties would be required to determine the long-term effects of these higher salt levels.

Regardless of the stand age and the depth of soil cover, roots continued to grow into the OB material. Given the saline-sodic nature of the OB, the low tolerance of many boreal tree species to salts and Na and the young age of these trees growing at the sites, leads us to question which species is responsible for this small fraction of root length at this depth. Although spruce and aspen roots have been reported to 3 m depth, other weedy or pioneer species present in the understory may also develop roots to these depths. Further work is required to determine which species is growing in these high salt layers.

The forest stands on these reclaimed mine sites were young and as such it is difficult to evaluate the full extent or possibilities for root growth and distribution. The sites are still relatively young and have not approached equilibrium with respect to the hydrologic systems, salt fluxes, and nutrient balances along with the vegetative communities. Saline forest environments do exist in limited locations around Alberta, and as long as the high salinity conditions are restricted to deeper depths in the soil profiles of these reclaimed sites then there is potential for forests to develop. It will be important to monitor the effects of the interface layer and OB on upward salt migration and hence its impact on root growth and vegetation development for these reclaimed sites.

4 ASSESSING ROOT ACTIVITY OF BOREAL SPECIES IN RECLAIMED OILSAND MINE SOILS USING A STRONTIUM TRACER

4.1 Introduction

Surface mining of oil sands in the boreal forest region of Alberta requires the disruption and reconstruction of huge tracts of land. Much of the overburden (OB) material that is removed in the mining process is highly saline and sodic in nature. When reclaimed, this OB material is capped with either about 1 m of layered peat and mineral soil, or a mixture of the two, and typically planted to upland boreal species. The properties of the OB material make it an unfavorable environment for the growth of tree roots, given the higher concentration of salts and sodium which most boreal species do not tolerate (Howat, 2000). Forest vegetation, however, has developed naturally in strongly saline landscapes of Alberta where the salts occur below the rooting zone (Purdy et al., 2005). In the previous chapter, a small proportion of roots from the mixedwood forest stands on reclaimed oil sand mine sites were found growing into the saline-sodic overburden (SSOB), although the plant species could not be identified.

In the boreal forest, tree roots are dominantly present in the upper 30 cm of the soil, however, they also extend deeper into the profile. For example, white spruce [wS; *Picea glauca* (Moench) Voss] roots have been found to 120 cm deep, while trembling aspen (tA; *Populus tremuloides* Michx.) and jack pine (jP; *Pinus banksiana* Lamb.) roots were recorded to a depth of 2 m and on average rooted to 1.7 m (Strong and La Roi, 1983a; Van Rees, 1997). A depth of 1.3 m was more typical for tree roots in this region and for tA on clay loam, maximum root depth was about 95 cm after 20 years (Strong and La Roi, 1983a). Jack pine and tA growing on sand showed increasing rooting depths with increasing stand age, while aspen on clay loam soils did not show the same linear trend (Strong and La Roi, 1983b). Regardless of soil texture, root density near the soil surface decreased with increasing stand age for the tA growing on both sand and clay loam.

On a reclaimed site, wS or jP may grow to depths equal to or deeper than the interface with the overburden material. However, the reclaimed sites at Syncrude Canada Ltd. (SCL) in northern Alberta and the plantations growing on them are quite young and species with faster growing root systems may be more likely to achieve soil depths of 1 m at a younger age. Jack pine trees are known to focus their root system development in the first few years towards a taproot followed by lateral branching in the next couple years (Rudolph and Laidly, 1990). Research conducted by Macyk and Richens (2002) found greater maximum rooting depths for several reconstructed sites (84 cm) compared to undisturbed sites (68 cm), although tap and vertical roots were reported to greater depths on the older undisturbed sites (beyond 1.2 m) versus the younger reconstructed sites (<90 cm).

Tracer studies are often used to help identify plant species which have roots actively growing at various depths in the soil profile (Soileau, 1973; Pinkerton and Simpson, 1979; Van Rees and Comerford, 1986, Capo et al., 1998). A tracer must be chemically similar to a required plant nutrient and taken up in the same manner, although of little significance as a nutrient itself; it must be non-toxic to the plant, not leachable in the soil, and have only a small background concentration within the soil (Pinkerton and Simpson, 1979; Capo et al., 1998). Strontium is a tracer which behaves much like calcium (Ca) due to its similar chemical nature. It is a divalent cation with an ionic radius close to that of Ca (Capo et al., 1998). As such, Sr can be taken up by the plant and incorporated into the plant tissues. Numerous researchers have conducted studies using Sr (in chloride, nitrate, or radioactive forms) to examine the soil, plant, or ecosystem pools, cycles, fluxes, distributions, or effects on Sr and Ca. For example, rooting depths and/or distributions of plants have been quantified (Fox and Lipps, 1964; Evans and Dekker, 1965; Soileau, 1973; Tikhomirov and Sanzharova, 1978; Pinkerton and Simpson, 1979; Fitter, 1986; Van Rees and Comerford, 1986; Mamalos and Veresoglou, 2000; Casper et al., 2003), and plant nutrient absorption zones, community structure, or competition for nutrients determined (Soileau, 1973; Tikhomirov and Sanzharova, 1978; Fitter, 1986; Mamalos et al., 1995; Dambrine et al., 1997; Mamalos and Veresoglou, 2000; Casper et al., 2003; Pecháčková et al., 2003). The internal translocation of Sr versus Ca, uptake, distribution, or accumulation of Sr versus Ca into different plant parts have been investigated using Sr tracers (Handly and Overstreet, 1963; Rasmusson et al., 1963; Hutchin and Vaughan, 1967; Creger and Allen, 1969; Tanaka and Woods, 1973; Poszwa et al., 2004) as have the fluxes, pools, and cycling of Ca or Sr through ecosystems (Poszwa et al., 2004; Poszwa et al., 2000; Dasch et al., 2006; Drouet et al., 2005), and the general soil properties, plant preferences, or genotypic effects on Sr uptake concentrations, rates, or transfer factors (Rediske and Selders, 1953; Romney et al., 1960; Queen et al., 1963; Hutchin and Vaughan, 1967; Burström, 1983; Roca and Vallejo, 1995; Veresoglou et al., 1995; Tsialtas et al., 2003; Dasch et al., 2006).

The objective of this study was to identify which plant species had their root systems growing in reclaimed SSOB and tailings sand (TS). In order to achieve this objective, a Sr tracer was used. The null hypothesis, therefore, was that rooting depth and activity of wS and jP were not influenced by the reclamation material.

4.2 Material and Methods

All sites are located on reclaimed landscapes at the SCL Mildred Lake Mine site, approximately 40 km north of Fort McMurray, Alberta, Canada. Based on climate data for the period 1971 to 2000 (Environment Canada, 2005), the mean annual temperature is 0.7°C with an average January temperature of -18.8°C and average July temperature of 16.8°C. The mean annual precipitation is 455.5 mm with 342.2 and 155.8 mm as rainfall and snowfall, respectively.

Because many of the rainstorm events are localized, rainfall at the mine site can differ from rainfall data collected at the Environment Canada weather station at the Fort McMurray airport. Weather data collected from a station at one of the reclaimed sites near the areas used in this study is presented in Appendix A for the years 2003 and 2004. An additional comparison with the rainfall data available from Environment Canada is also presented. The rainfall received in 2003 was typical of an average year, but 2004 was drier, receiving over 100 mm less rainfall than normal.

4.2.1 Site Descriptions

Root activity was evaluated for two jP and two wS stands, with each species growing on a SSOB and a TS site for a total of four sites (jP-SSOB, jP-TS, wS-SSOB, wS-TS). Site maps and plot layouts for the S2 North, Mildred Lake Settling Basin (MLSB) Cell 19, MLSB Cell 16 and S27 sites can be found in Appendix B.

4.2.1.1 S2 north

Growing on the north facing slope of S2 was a wS stand with SSOB as the subsoil. Capping of the 10 ha site was completed in 1993 with 90 cm of mineral soil and 10 cm of peat. Tree seedlings were planted in both 1993 and 1994. In 1993, 6349 wS were planted with a target of 3489 trees ha^{-1}. In 1994, 2000 trees ha^{-1} planting over 2.8 ha. All $SrCl_2$ treatments were applied at this site on 16 August 2003.

4.2.1.2 MLSB cell 19

At MLSB, cell 19 contained a wS stand growing on TS with a NE aspect, planted in 1994. The site was capped with 50 cm of mineral soil (from NW quadrant), 20 cm muskeg (NT-2 stockpile) or with 70 cm of direct placement material (from NW quadrant). Strontium chloride treatments for this study were applied 18-19 August 2003. There was no information available in regards to planting density.

4.2.1.3 MLSB cell 6

This jP stand at MLSB Cell 6 grew on a TS step-out. This area was quite level, but there was a slight WSW slope. Capping occurred in 1991 with direct placement of material to a targeted depth of 70 cm. This site was planted with 32,000 jP seedlings in 1992 (estimated density of 3200 stems ha^{-1}). Strontium chloride treatments were applied 18-22 August 2003.

4.2.1.4 S27 (bison hill)

The jP site behind the bison pasture was capped in 1993 by direct placement of 1 m of mineral soil. Another part of this area was capped in 1994 with a target of 90 cm of mineral soil and 10 cm of peat. The site (20.5 ha) was planted with jP in 1994, to a target density of 2000 trees ha^{-1}. This slope was S-facing and the $SrCl_2$ treatments were applied 19-21 August 2003.

4.2.2 Experimental Design and Treatments

To determine which plants growing on reclaimed soils were extending roots into the SSOB, a tracer study was conducted. Strontium chloride was used as an indicator of the root activity or the uptake of water and nutrients. Strontium behaves much like Ca, and is taken up from the soil by plant roots and translocated into the leaves and wood (Capo et al., 1998). Higher tissue levels of Sr in treated plots compared to the control plots suggest the presence of active roots in the layer of Sr placement. Different plant species have different root forms that will access water and nutrients at different depths. By placing the $SrCl_2$ at specific depths (i.e., in the OB or TS) the species of interest can be identified. Only species with actively growing roots in the location of the added $SrCl_2$ will take up the added Sr, resulting in greater foliar Sr concentrations, allowing for identification of the plant species rooting into the SSOB.

Root activity was measured using granular $SrCl_2$, similar to the procedures used by Van Rees and Comerford (1986) and Van Rees (1997). Three $SrCl_2$ treatments, replicated three times, were used to study root activity: control (C), surface broadcast (B), and depth placement (D). All treatment plots (2 m x 1 m) around randomly selected trees were established at distances sufficient to prevent interaction between trees in the other treatments (at least 15 m). The actual distances depended on the size of the available site (Appendix B). The upper slope landscape position was selected at each site except for MLSB Cell 6 where the area was level. The control plots had no $SrCl_2$ added. The broadcast treatments had 120 g of $SrCl_2$ broadcast manually across the plot by spreading two 60 g amounts, one on each 1 m^2 area on either side of the tree. The treatment was watered with 1 L of water over each square meter area. Strontium chloride was placed at depth by augering twelve holes with a Dutch auger (2.5 cm diameter) to 15 cm into the overburden or an approximately equivalent depth in the TS. At S2 North, the depth of the overburden ranged from 85 to 100 cm; at S27 the range was from 65 to 100 cm; at MLSB Cell 6 the values ranged from 55 to 70 cm for tailings sand and all holes were augered to about 85 cm depth; at MLSB Cell 19 the range was 60 cm to greater than 100 cm deep for the tailings sand and all holes were augered to 100 cm.

The soil from augering was kept aside to backfill the hole after adding the $SrCl_2$. The $SrCl_2$ was placed at depth by pouring it through a PVC pipe (1.9 cm diameter) inserted into the hole, which prevented contamination along the profile. A small amount of water (250 mL) was poured through the tube to remove any $SrCl_2$ from inside the tube and make the Sr accessible in soil solution. Each hole was backfilled with the augered material that had been saved.

4.2.3 Field Methods

Background levels of Sr were determined from foliage collected on August 14-15, 2003 from all the trees in the experiment as well as from the individual understory vegetation and volunteer tree species on or near the treatment plots prior to the placement of the Sr. Conifer needles were collected by hand from the trees' current year's growth (upper third of the crown). Table 4.1 lists the vegetation (conifer and understory) collected from each of the different sites. The height of the tallest leader for each tree was also measured. Tree needles were only collected on October 18, 2003 and again one year after Sr application on August 6-7, 2004 along with tissue samples of all the understory material.

Not all understory species occurred in all the plots at a given site (Table 4.1). In order to present some of the treatment data where the control plots did not contain the understory species, relative reference controls were obtained by sampling from the general area of the plots in the fall of 2004 and analyzing them in the same manner as the other samples to act as representative controls.

4.2.4 Laboratory Methods

Tissue samples were oven-dried at $40^{o}C$ for 1 wk and then ground. Samples (0.25 g) were digested using a single modified digestion with sulfuric acid and hydrogen peroxide (Thomas et al., 1967). Two standards (SRM 1575 Pine Needles NIST, Gaithersburg, MD, USA) were also analyzed. Solutions were analyzed for Sr using a Varian SpectrAA-220 spectrometer (Varian Australia Pty Ltd., Australia) equipped with a SPS 5 Sample Preparation System. Every sample and standard was diluted with a KCl solution and analyzed according to standard procedures for N_2O acetylene flame at a wavelength of 460.7 nm (Varian, 1989).

Table 4.1. Number of plots out of nine containing each species of vegetation sampled for baseline strontium levels across all sites.

Site	wS†	tA	bP	wi	dw	jP	gr	cl	da	sth	bft	rb	sb	pv	gb	bb	kk	fw
S2	9	1	8	2	1		5	7	2	2								
MLSB Cell 19	9		8		1		5	1	1	7	2	2						
S27						9	8	1		7		1						2
MLSB Cell 6			2			9	3	4		2			8	1	2	1	3	1

† wS - white spruce (*Picea glauca*); tA – trembling aspen (*Populus tremuloides* Michx.); bP – balsam poplar (*Populus balsamifera* L.); wi – Willow (*Salix* L.); dw – dogwood (*Cornus sericea* L.); jP – jack pine (*Pinus banksiana*); gr – grasses (various); cl – clover (*Melilotus officinalis* (L.) Lam. and *M. alba* Medikus); da – dandelion (*Taraxacum offininale* G.H. Weber ex Wiggers); sth – sow thistle (*Sonchas oleraceus* L.); bft – bird's foot trefoil (*Lotus corniculatus* L.); rb – raspberry (*Rubus* L.); sb – strawberry (*Fragaria* L.); pv – pea vine (*Lathyrus* L.); gb – goose berry (*Ribes* L.); bb – buffalo berry (*Shepherdia* Nutt.); kk – kinnikinnick (*Arctostaphylos uva-ursi* (L.) Spreng.); fw – fireweed (*Chamerion angustifolium* (L.) Holub). (Integrated Taxonomic Information System, 2008).

4.2.5 Statistical Analysis

All statistical analyses were performed using SPSS Version 14 (Chicago, Illinois). Each tree species was examined for differences in foliar Sr concentrations amongst the three Sr treatments both in the fall and one year later using ANOVA. Post hoc tests were done using the LSD procedure.

4.3 Results

4.3.1 Tree Height

Average tree height for each species varied by site, but was not significantly different. The jP trees were taller, averaging 304 and 347 cm at S27 and Cell 6, respectively, while the wS reached average heights of 184 cm at S2 and 216 cm at Cell 19 (Table 4.2).

4.3.2 Sr Uptake by Trees

Initial background Sr concentrations for wS (31.0 ± 5.3 µg g^{-1}) were more than three times that of jP (7.9 ± 1.8 µg g^{-1}). Within individual tree species, there were no differences in background Sr concentrations prior to Sr application between TS and OB sites (Appendix F).

There were no significant differences between treatments for Sr concentrations in either 2003 or 2004 for the jP trees growing on OB (at S27). Average Sr concentrations for jP needles from S27 were 0.5 ± 0.5 and 2.2 ± 1.0 µg g^{-1}, for two months and one year after $SrCl_2$ application, respectively (Figure 4.1 and 4.2). At Cell 6 (TS site), foliar Sr concentrations for samples collected two months after $SrCl_2$ application showed a significant difference between treatments. The LSD tests revealed that the broadcast treatment had significantly greater ($p < .10$) foliar Sr levels (4.75 ± 2.33 µg g^{-1}) than either the control (2.07 ± 0.86 µg g^{-1}) or depth (1.35 ± 0.28 µg g^{-1}) treatments (Figure 4.1). Similar to the OB site, foliar Sr concentrations determined for needles collected one year after $SrCl_2$ application (Figure 4.2) showed no significant differences between treatments for the TS site (Cell 6) and averaged 3.4 ± 1.2 µg g^{-1}.

White spruce showed no response to the broadcast Sr treatments compared to the control at either S2 or Cell 19 two months after application ($p > .10$). However, the

Table 4.2. Mean tree height (± 1 standard deviation, SD) for each conifer species at each reclaimed site.

Site	Treatment† C	B	D	Site Average
	------------------------ cm	------------------------		
		White spruce		
Cell 19	203 ± 21	198 ± 33	249 ± 40	216 ± 37
S2	193 ± 25	192 ± 25	168 ± 39	184 ± 29
		Jack pine		
Cell 6	355 ± 40	356 ± 76	330 ± 42	347 ± 49
S27	318 ± 30	294 ± 46	299 ± 22	304 ± 32

† C - control, B - broadcast, D - placement at depth.

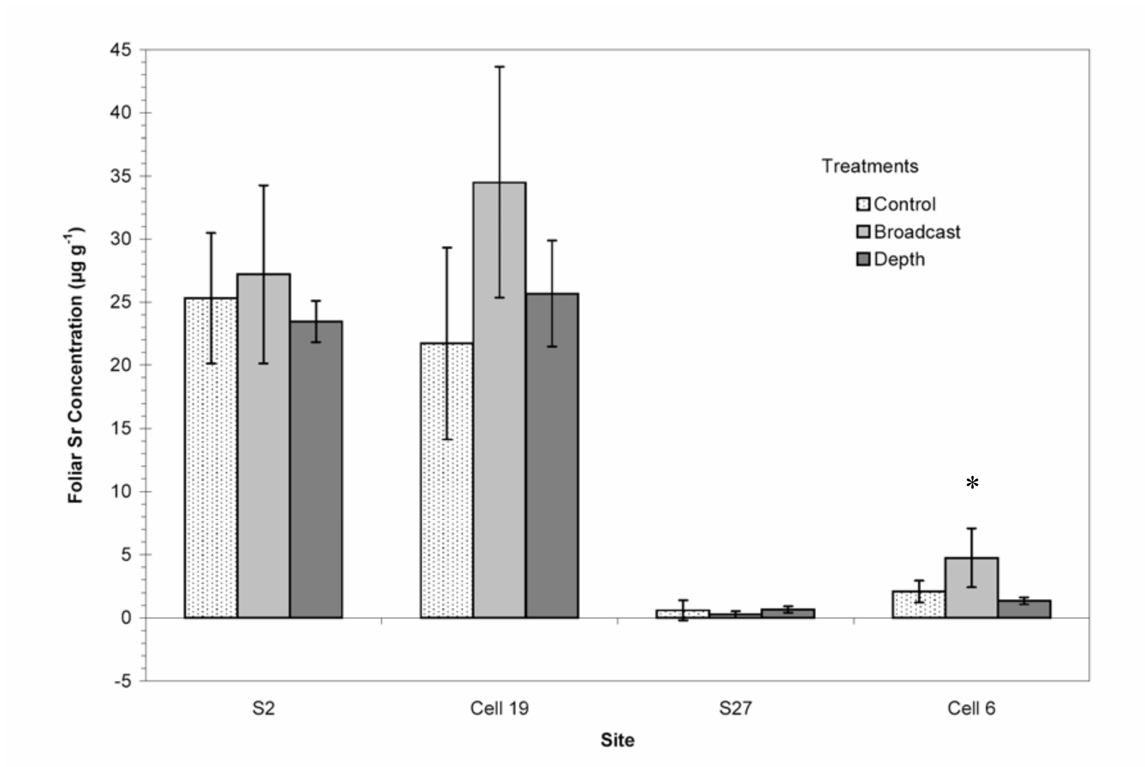


Figure 4.1. Mean foliar strontium concentrations for white spruce (S2 and Cell 19) and jack pine (S27 and Cell 6) needles collected two months after (October 2003) $SrCl_2$ treatment applications. Error bars indicate ± 1SD. * indicates statistical difference at $p < .10$ among the treatments within a site according to LSD.

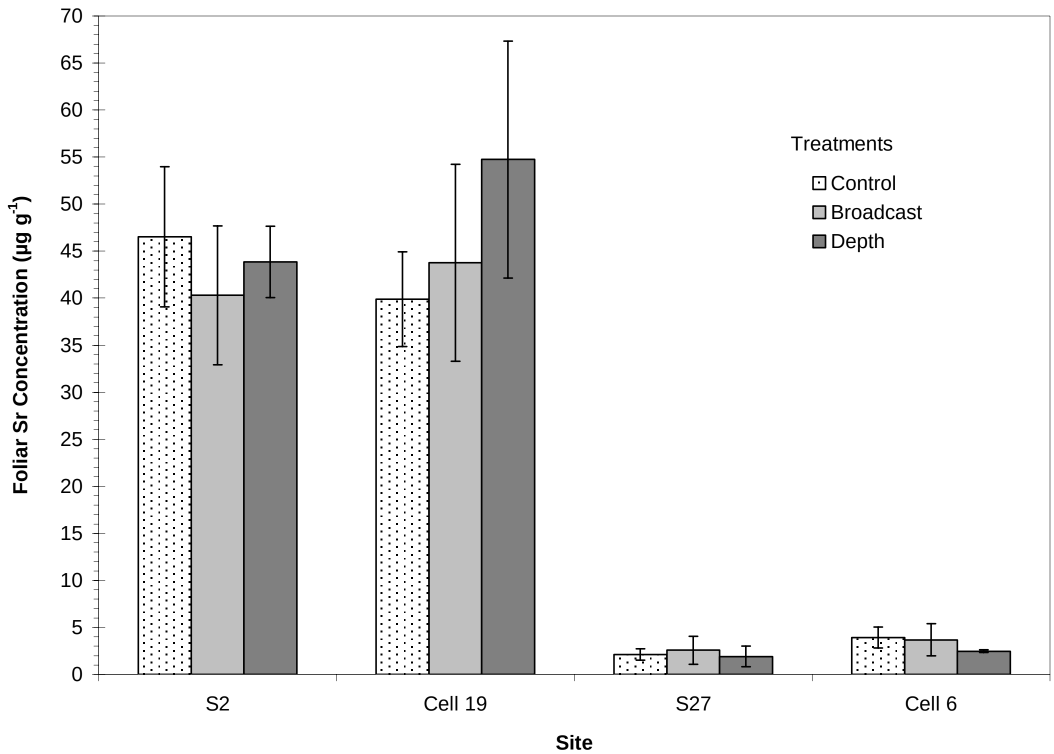


Figure 4.2. Mean foliar strontium concentrations for white spruce (S2 and Cell 19) and jack pine (S27 and Cell 6) needles collected one year after (August 2004) $SrCl_2$ treatment were applied. Error bars indicate ± 1SD.

broadcast treatments did have higher concentrations of Sr in the tree needles at each site (Figure 4.1). One year after Sr application, wS showed no significant response to the broadcast or depth treatments compared to the control at either site (Figure 4.2), although the depth treatment at Cell 19 had greater Sr concentration in the needles than either the broadcast or control treatments. Average Sr concentrations in the wS needles across all treatments were 25.3 ± 4.8 and 27.3 ± 8.5 µg g^{-1} (two months after) and 43.6 ± 6.2 and 46.1 ± 10.9 µg g^{-1} (one year later) for sites S2 and Cell 19, respectively.

4.3.3 Sr Uptake by Understory

All understory species contained greater amounts of foliar Sr than the jP trees, and in general, understory species contained equal or greater Sr concentrations than the wS trees (Appendix F). Strontium concentrations measured in the tissue samples collected from 2004 (one year after $SrCl_2$ application) are shown for the different treatments where available at each site in Table 4.3 to 4.6. Statistical differences between treatments could not be determined due to the lack of replication. Few understory species occurred in all treatment plots, and as such, not all treatments are shown for each species.

Several species showed much higher uptake of Sr after the broadcast treatment than either wS or jP. For strawberry at Cell 6 (Table 4.5), Sr uptake from the broadcast treatment (658.5 ± 214.4 µg g^{-1}) was about seven times greater than the control (82.1 ± 21.9 µg g^{-1}). Grass spp., dandelion, bird's foot trefoil, kinnikinnick, and clover occurred in broadcast treatment plots and also showed large increases in levels of Sr. Fireweed Sr content increased from control values of 44.0 and 97.1 µg g^{-1} to 67.3 and 198.6 µg g^{-1} in broadcast treatments (not replicated). A smaller response was observed at S27 (Table 4.3) versus Cell 6 (Table 4.5).

Some of the understory species had greater Sr uptake in response to the depth treatment application over the control treatment. The species that responded to Sr applied at depth included clover, sow thistle, and grass spp. (refer to Table 4.3 through Table 4.6). Dandelion showed an increase in uptake at Cell 19 (Table 4.4), but not at S2 (Table 4.6). Differences from site effects or subsoil materials cannot be determined as there were too few replications. All species which had greater Sr content with the depth treatment also had displayed increased Sr uptake for the broadcast treatment.

Table 4.3. Mean foliar Sr concentrations (± 1 SD) determined for selected understory species in the treatment plots at S27.

	$SrCl_2$ Treatment		
Species†	Control‡	Broadcast	Depth
	---------------------------- μg g^{-1} ------------------------		
cl	53.7 (1)§		76.4 (1)
fw	44.0 (1)	67.3 ± 37.5 (2)	
gr	15.1 ± 11.9 (2)	69.1 ± 20.6 (3)	26.4 ± 10.6 (3)
sth	40.2 ± 18.6 (2)	228.3 ± 199.9 (3)	40.7 ± 5.9 (2)

† cl – clover (*Melilotus officinalis* (L.) Lam. and *M. alba* Medikus); fw – fireweed (*Chamerion angustifolium* (L.) Holub); gr – grasses (various); sth – sow thistle (*Sonchas oleraceus* L.) (Integrated Taxonomic Information System, 2008).

‡ Control samples for cl and fw were obtained from outside the plots.

§ Numbers in brackets represent the number of plot samples the species was found in.

Table 4.4. Mean foliar Sr concentrations (± 1 SD) determined for selected understory species in the treatment plots at MLSB Cell 19.

	$SrCl_2$ Treatment		
Species†	Control‡	Broadcast	Depth
	---------------------------- μg g^{-1} ------------------------		
bft	77.8 (1) §	300.2 (1)	70.2 (1)
bP	27.7 ± 4.9 (2)	42.4 ± 15.8 (3)	24.2 ± 7.0 (2)
cl	91.8 (1)	217.6 (1)	
da	56.0 (1)		90.3 (1)
gr	41.9 ± 5.9 (2)	50.3 (1)	
rb	26.9 (1)	50.7 (1)	
sth	50.0 ± 7.0 (3)	248.1 (1)	110.9 ± 111.6 (3)

† bft – bird's foot trefoil (*Lotus corniculatus* L.); bP – balsam poplar (*Populus balsamifera* L.); cl – clover (*Melilotus officinalis* (L.) Lam. and *M. alba* Medikus); da – dandelion (*Taraxacum offininale* G.H. Weber ex Wiggers); gr – grasses (various); rb – raspberry (*Rubus* L.); sth – sow thistle (*Sonchas oleraceus* L.) (Integrated Taxonomic Information System, 2008).

‡ Control samples for bft, cl, and da were obtained from outside the plots.

§ Numbers in brackets represent the number of plot samples the species was found in.

Table 4.5. Mean foliar Sr concentrations (± 1 SD) determined for selected understory species in the treatment plots at MLSB Cell 6.

	$SrCl_2$ Treatment		
Species†	**Control‡**	**Broadcast**	**Depth**
	---------------------------- $\mu g\ g^{-1}$ ------------------------		
bP	63.9 (1) §	123.9 (1)	
cl	84.9 (1)	349.3 (1)	138.1 ± 43.1 (3)
fw	97.1 (1)	198.6 (1)	
gr	37.9 (1)		29.9 ± 13.5 (2)
kk	27.5 (1)	155.4 (1)	20.8 (1)
sb	82.1 ± 21.9 (3)	658.5 ± 214.5 (3)	103.5 ± 17.3 (2)
sth	92.2 (1)	443.9 (1)	119.5 (1)

† bP – balsam poplar (*Populus balsamifera* L.); cl – clover (*Melilotus officinalis* (L.) Lam. and *M. alba* Medikus); fw – fireweed (*Chamerion angustifolium* (L.) Holub) gr – grasses (various); kk – kinnikinnick (*Arctostaphylos uva-ursi* (L.) Spreng.); sb– strawberry *(Fragaria* L.); sth – sow thistle (*Sonchas oleraceus* L.). (Integrated Taxonomic Information System, 2008).

‡ Control samples for bft, cl, and da were obtained from outside the plots.

§ Numbers in brackets represent the number of plot samples the species was found in.

Table 4.6: Mean foliar Sr concentrations (± 1 SD) determined for selected understory species in the treatment plots at S2.

	$SrCl_2$ Treatment		
Species†	**Control‡**	**Broadcast**	**Depth**
	---------------------------- $\mu g\ g^{-1}$ ------------------------		
bP	26.6 ± 3.3 (2) §	36.5 ± 11.8 (2)	29.1 ± 3.5 (3)
cl	122.0 (1)	261.6 ± 48.9 (3)	141.7 ± 34.3 (2)
da	57.8 (1)	359.0 (1)	59.9 (1)
gr	22.5 ± 2.4 (2)	144.2 ± 8.2 (2)	33.4 (1)
sth	63.6 (1)	252.8 (1)	
tA	35.2 (1)	64.0 (1)	
wi	53.9 (1)		48.4 (1)

† bP – balsam poplar (*Populus balsamifera* L.); cl – clover (*Melilotus officinalis* (L.) Lam. and *M. alba* Medikus); da – dandelion (*Taraxacum offininale* G.H. Weber ex Wiggers); gr – grasses (various); sth – sow thistle (*Sonchas oleraceus* L.); tA – trembling aspen (*Populus tremuloides* Michx.); wi – Willow (*Salix* L.) (Integrated Taxonomic Information System, 2008).

‡ Control samples for bft, cl, and da were obtained from outside the plots.

§ Numbers in brackets represent the number of plot samples the species was found in.

4.4 Discussion

Similar to other research results, foliar Sr content was observed to vary with the species, both for the conifers and the understory plants tested (Rediske and Selders, 1953; Rasmusson et al., 1963; Evans and Dekker, 1965; Vose and Koontz, 1959; Van Rees and Comerford, 1986; Veresoglou et al., 1995; Veresoglou et al., 1996; Van Rees, 1997; Mamolos and Veresoglou, 2000; Poszwa et al., 2000; Pecháčková et al., 2003; Poszwa et al., 2004). Variation within a species was reported by Rasmusson et al. (1963) who noted differences in ^{89}Sr uptake among separate barley and wheat genotypes. Pinkas and Smith (1966) found that Sr transport from the roots to shoots differed between varieties of barley, thus resulting in different levels of Sr in aboveground tissues. Pinkerton and Simpson (1979) also observed the absorption differences between species and noted the necessity to have a control for each species when using a tracer such as Sr. In this study, we were able to achieve this by collecting Sr data for species in non-treated plots in the experiment.

Among the differences noted between species tested in this study were the exceptionally low levels of Sr in jP. Franklin et al. (2002) conducted studies with jP seedlings using consolidated tailings water (Sr = 1.5 mg·L^{-1}) from Syncrude Canada in which Sr levels significantly increased from 3.20 to 6.87 µg g^{-1} (dry weight) for the control and treated seedlings, respectively. Poszwa et al. (2004) found that at both sites they tested, Sr concentrations in trunk wood, twigs, and needles of Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.) were always higher for spruce than for pine. Strontium concentrations in spruce and pine needles were 35.4 and 3.8 µg g^{-1} for a Podzol site and 23.5 and 1.5 µg g^{-1} for a peat site, respectively. Strontium concentrations of slash pine studied on a Florida Spodosol ranged from 3 to 12 µg g^{-1} when all Sr treatments and needle flushes were included (Van Rees and Comerford, 1986). Ponderosa pine examined in the Chaco Canyon, New Mexico had Sr levels of <15 µg g^{-1} (Reynolds et al., 2005). Although Sr concentrations for Scots pine trees in Latvia varied depending on methods used to wash the needles, the values fell within 2.3 and 5.2 µg·g^{-1} (Viksna et al., 1999). Scots pine in northern Europe had foliar Sr content of 4.3 µg g^{-1} (Reimann et al., 2001) and generally <10 µg·g^{-1} in southern Sweden (Wallander, 2000), while Norway spruce had foliar Sr concentrations of 18.2 µg g^{-1}

(Reimann et al., 2001). White spruce needles examined in Switzerland and France had Sr concentrations between 4.38 and 26.3 μg g^{-1} (Poszwa et al., 2000). The same species in the boreal forest of Saskatchewan had needle Sr concentrations from 10.40 to 13.67 μg g^{-1} in untreated control plots (Van Rees, 1997). The low Sr values determined for jP needles in this study were similar to those reported by Franklin et al. (2002) and similar to nearly all those determined for other pine species. The values measured in the wS were above those reported by Van Rees (1997), but similar to the higher values determined by Poszwa et al. (2000) and those determined for Norway spruce (Poszwa et al., 2004).

Depending on the site, sampling time, and Sr treatment, foliar Sr concentrations for the jP showed both significant and non-significant differences among treatments. A significant increase in foliar Sr concentration above the control was observed in the broadcast treatment for the jP growing on TS. The lack of increased uptake of Sr from the broadcast treatment by jP on OB, when all other species in the plots responded favorably, leads to an inconclusive result. The suggestion that no roots were actively growing near the surface is unlikely. Rudolph and Laidly (1990) describe the jP tree lateral root system as occurring primarily in the upper 46 cm of the soil and much of that within the first 15 cm. Examination of forested sites in the Fort McMurray area found 11 out of 12 to have the greatest weight of roots in the 0-15 cm depth interval (Macyk and Richens, 2002), in agreement with the values presented by Strong and La Roi (1983a).

Although no increase in foliar Sr concentration was measured for the depth treatment, it does not conclusively indicate that jP roots were not growing at that depth. Roots may grow to 2.7 m on well-drained soils (Rudolph and Laidly, 1990). Research summarized by Stone and Kalisz (1991) provided maximum rooting depths for jP at 2.0 to 2.9 m with one exception which occurred on a clay substrate. Macyk and Richens (2002) summarized jP tree rooting depths for reconstructed and undisturbed sites at or near the Syncrude oil sand mine operations in northern Alberta and reported maximum rooting depths ranging from 90 to >130 cm, the latter being a value commonly found in the research conducted by Strong and La Roi (1983a), although they also reported depths up to a maximum of 2 m.

The taproots from jP trees excavated by Strong and La Roi (1983a) were simple until branching at 50-90 cm depth before descending further. If this typical rooting occurred on the sites used in this study, the roots would have branched just above the Sr placement. It may be possible that the Sr additions were not placed close enough together to ensure roots reached the enriched area. Van Rees (1997) had used more $SrCl_2$ (200 g versus 120 g in this study) for the surface and depth treatments; and the $SrCl_2$ for the depth treatment was distributed amongst more holes (25 versus 12 in this study) over the same size plot area (2 m^2). For the older site where no significant Sr uptake was observed for wS or tA, it was proposed that the Sr was likely diluted within the large (85-110 yr old) trees. However, on the youngest site (10 yr – similar to this study), wS and tA both took up significantly higher levels of Sr from the surface treatment even after a second year of growth. Using a higher concentration of $SrCl_2$ and placing it into more holes may have been required to see an uptake response by jP in our study; however, we wanted to minimize disruption of the soil and root profiles. Additionally, Van Rees and Comerford (1986) used only 80 g of $SrCl_2$ spread over 3.3 m^2 or placed into 10 holes in their plots and found increased uptake for two needle flushes by mature slash pine. In studies by Bockheim and Leide (1991), jP foliar Ca increased through the entire growing season. If Sr behaved in the same manner, we would have anticipated continued increases through to October, provided sufficient amounts were available for uptake where roots were actively growing. Calcium concentration of litterfall from a jP forest in Ontario also showed a continued increase from July to October (Foster and Gessel, 1972).

Alternatively, there is the potential that competition from other vegetation, whether in terms of root growth and architecture or the temporal and spatial differences in nutrient requirements and growth habits (Alban, 1982; Fitter, 1986; Van Rees and Comerford, 1986; Helmisaari, 1992a; 1992b; Mamolos et al., 1995; Van Rees, 1997; Mamolos et al., 2000; Pecháčková et al., 2003), can largely influence the uptake of Sr from the soil. Differences or limitations in Sr uptake can be related to the plant and soil relationships with Ca and Sr. For example, the preferential uptake or translocation of Ca, preferential foliar leaching of Sr, or the presence of competing ions in the soil-plant system could all influence the success of a Sr tracer experiment (Hutchin and Vaughan, 1968; Veresoglou et al., 1995; Poszwa et al., 2000; Ehlken and Kirchner, 2002; Poszwa et al., 2004). General agronomic factors play a role in a plant's uptake response, including general soil properties (organic matter content, CEC, pH, texture), salinity stress, micro-organisms, fertilization, temperature and moisture conditions (Evans and Dekker, 1965; Roca and Vallejo, 1995; Veresoglou et al., 1996; Mamolos et al., 2000; Ehlken and Kirchner, 2002; Franklin et al., 2002; Tsialtas et al., 2003). Each species will differ in the time and depth at which the root system is active in the soil and these aspects may in turn be altered by competing vegetation, compounding the possible influences on Sr uptake (Mamolos et al., 1995). Competition for the Sr in the jP sites by understory plants either temporally (earlier root growth) or spatially (more roots near the soil surface to access resources) would be difficult to interpret. A possible explanation for a lack of response by jP to Sr additions could be that the root systems of the trees were poorly developed from planting; a possibility which could easily be examined by excavating and evaluating the tree root systems. Other potential effects such as dilution of Sr within the new growth of the tree would be more difficult to examine without the use of isotopes.

Similar to jP, wS did not respond well to the broadcast Sr treatment measured one year later. However, there was one notable, although non-significant increase in Sr concentration for the broadcast treatment two months later at Cell 19. We suspect that there were actively growing roots near the surface, but that competition was likely involved as no significant increase in foliar Sr was observed for the broadcast treatment at S2 as well. The fall sampling two months after Sr application was initially intended to catch any Sr uptake prior to winter. It became the only indication of any increase in uptake found for the wS for the broadcast treatments at the two sites suggesting that either additional sampling times would be needed to properly capture the uptake, that larger amounts of $SrCl_2$ should be applied, or that further uptake may have been limited by competition from understory plant roots in the spring or diluted by the new tissue growth. Even two years after a broadcast treatment, wS in Saskatchewan showed increased foliar Sr concentrations (Van Rees, 1997).

At Cell 19, the greatest Sr uptake, although not significant, occurred for the depth treatment. It is possible that the wS roots have grown to 1 m in the tailings sand; however, due to the lack of response of the broadcast treatment over the control, the results were inconclusive. Schultz (1969, from Van Rees, 1997) found wS roots grew deeper into sands than sandy- and silt-loams. Likewise, Strong and La Roi (1983b) had reported greater maximum rooting depths for all forest stands on coarse textured soils and measured jP roots to 130 cm on sand. They described heart roots from wS to enlarge and elongate with tree age, to 1 m for a 28 m tall tree, and become more developed on sand than fine-textured soils (Strong and La Roi, 1983b). In younger stands, these roots had not penetrated as deeply and in the youngest stand (19 yr) they were not present. Nienstaedt and Zasada (1991) report the common rooting depth for wS as between 90 and 120 cm with taproots extending to depths of 3 m. This is in agreement with maximum rooting depths provided by Stone and Kalisz (1991). Van Rees (1997) recorded wS roots to 120 cm depth in Saskatchewan, which would be of similar depth to the Sr placement at Cell 19.

The greatest response observed with the broadcast and depth applications of Sr was in relation to the understory species, although they were not replicated and as such, significant differences could not be determined. High levels of root activity near the soil surface was reported by numerous researchers including Tikhomirov and Sanzharova (1978) who noted that different species absorbed nutrients from different soil layers corresponding to their specific root distribution. In this study, most plants had foliar Sr content <100 $\mu g\ g^{-1}$. Under the broadcast treatment the tissue concentrations increased to >200 $\mu g\ g^{-1}$ for clover, bird's foot trefoil, dandelion, sow thistle, and strawberry, with the largest increases occurring at Cell 6.

Foliar Sr levels were higher for clover and sow thistle than the grasses. In studying pasture plants, Vose and Koontz (1959) reported greater uptake by all legumes over grasses, and that the amount of Sr and Ca taken up were directly related. Calcium levels for clovers were typically higher than grasses, leading to the same for Sr contents (Russell and Garner, 1959). Strontium uptake by clover was listed in relation to a variety of plants in a study by Romney et al. (1960), where turnip tops, millet, and Swiss chard had greater concentrations when grown on the same soil, while broccoli, soybeans, barley, oats, wheat, and spinach had less. At Cell 6, we saw high background Sr levels in several species. Grasses and kinnikinnick had the lowest foliar Sr concentrations, followed by fireweed and sow thistle which contained double the amount of Sr in their leaf tissue; whereas buffalo berry, pea vine, and strawberry had the highest concentrations of Sr, nearly quadrupling the low tissue contents of grasses and kinnikinnick, and clover, balsam poplar, and goose berry had three times the low foliar Sr concentrations (Appendix F).

There was greater Sr uptake for the depth treatment than for the control treatment by grasses, sow thistle, and clover. From the limited data collected, the grasses showed a higher uptake over the control at the OB sites and none at Cell 6. Sow thistle responded more at the TS sites and not at S27 (OB). Clover not only showed a greater uptake over the control for Cell 6, but also for both OB sites. White sweet clover develops a taproot quickly, which may reach 0.75 m by 7 wk and 1.8 m by 4 mo., resulting in a mature root system which is 1.5 to 2.4 m deep (Weaver, 1926). Numerous large and small branches with laterals are present also, adding to clover's ability to absorb water and nutrients from a large volume of soil. During the first year, clover, as an obligate biennial, would direct its energy into developing a strong root system and this root development would continue into late summer (Maggie Cole Illinois Department of Conservation, 1990). Thus, the potential period for Sr uptake by this plant would be extended and would increase its competitive ability for Sr uptake with the conifers at the sites. Sow thistle root systems were defined as creeping in the perennial species, while the annual sow thistle has a taproot (Darwent et al., 2004). Shallow horizontal rhizomes, within 12 cm of the surface, may grow 2 m in one season, while vertical roots can extend the same distance into the soil with new shoot buds up to 50 cm deep (California Department of Food and Agriculture, 2005). This root system would allow sow thistle, like clover, to access Sr applied both at the surface and at depth. Grasses, dependent upon the species, may also grow to great depths. Coupland and Johnson (1965) thoroughly describe the root systems for 14 different grass species and two sedges in the Saskatchewan prairie. Mean maximum rooting depths varied with species, soil zone, and slope from a low of 33 cm to a high of 165 cm. Variation in absorbance of Sr by grass species in Czech Republic was attributed to differences in root system and rhizome architecture (Pecháčková et al., 2003). All three of these plants (clover, sow thistle, and grasses) have root systems that would allow them to survive and reach the depths of Sr placement at both the TS and OB sites.

In the previous chapter we observed a small proportion of roots growing into the overburden material on mixedwood sites, but did not know what plant species was responsible for this growth. Although we studied only wS and jP sites for root activity, several of the understory species found at these four sites were also observed in the mixedwood sites used in the previous chapter. We believe that it is unlikely that the roots in the OB material were from the trees, but rather that deeper rooted understory species such as clover, grasses and sow thistle were responsible for this limited root growth in the OB. Clover is moderately tolerant of salinity (Henry, 2003), and all three understory species have extensive root systems. White spruce and jP roots, although able to grow to depths of the OB and TS interfaces, did not show definitive Sr uptake to support such a conclusion. These forest plantations were young and the root growth of the trees has likely yet to have taken advantage of occupying the entire soil profile.

4.5 Conclusions

Foliar Sr levels for jP trees were low regardless of the treatment application depth; however, two months after application, jP on TS (Cell 6) showed a significantly higher amount of foliar Sr than the control. This response was not observed at S27 which could have been the result of several factors: poor root system development, both lateral and taproots reducing the trees ability to access resources; dilution effects reducing the Sr concentration throughout the new growth of needles and branches to undetectable differences; or over-competition for limited resources by other vegetation. We did not investigate if the low levels were due to low Ca requirements of jP trees, competition, or some other mechanism.

Because there was no uptake response by wS to any of the Sr treatments at S2 or Cell 19, we cannot conclusively identify any root activity. Higher, although not significantly different, values were measured on the TS site (Cell 19) suggested that active roots were present near the surface, but that other factors were limiting their ability to access or take up the Sr. After one year, no wS needle samples were different between treatments for either site; however, the values observed for the depth treatment at Cell 19 were larger than any other treatments. Again, with no response to the broadcast treatments, the results were inconclusive. The localized increase measured in the fall for the broadcast treatment, but not at the end of a full growing season, suggests that either multiple sampling times were required to capture an increase, or that interference, competition, species preferences, soil properties, Sr dosage, or some other relationship might be affecting the Sr uptake by the trees. The only increases observed were on the TS site which may also suggest an influence of site or soil properties.

Foliar Sr concentration data, collected for the understory species, provided an indication of the larger Sr (Ca) users with roots near the soil surface and to a lesser extent those species which may be rooting at depth. Species with high Sr uptake on TS and/or OB substrates included strawberry, fireweed, grasses, dandelion, bird's foot trefoil, kinnikinnick, and clover. The higher Sr foliar levels in the depth treatment for species such as clover, sow thistle, and grasses suggests that these species are capable of rooting deeply in these materials as well as tolerating salinity in these substrates.

Although a small proportion of roots have been reported growing in the SSOB of the reclaimed sites at Syncrude Canada Ltd., the use of a stable Sr tracer was not able to conclusively identify if the tree species (jP or wS) were responsible. However, understory species such as clover, sow thistle, and grasses present at the sites may be the species rooting in the SSOB rather than the trees as indicated by the small increases in their foliar Sr content.

5 ROOT DEFORMITIES AND TAPROOT DEVELOPMENT OF PLANTED JACK PINE ON RECLAIMED OIL SAND MINESOILS

5.1 Introduction

Jack pine (jP; *Pinus banksiana* Lamb.) is one of the primary species being planted in the reclamation areas for Syncrude Canada Ltd.'s Mildred Lake mine site. Although often thought of as growing on poorer sandy soils, jP inhabit a variety of soil types within the Boreal region, ranging from sandy to clayey textures and nutrient poor to rich sites. The root systems of naturally regenerated or seeded jP typically consist of a dominant taproot and a symmetrical lateral root system radiating away from the tree base (Rudolph and Laidly, 1990). These laterals act as stays to keep the tree upright and prevent the stem from pivoting (Burdett et al., 1986).

Planted jP trees differ in their root morphology as cultural practices affect the symmetry, balance, constriction, coiling, taproot development, extent of deformation, and planting method (Long, 1978). Although referring to bareroot seedlings, Tinus (1978) summarized root system shape as a function of the tool used for planting, technique of the planter, soil properties and obstacles, and the slash and vegetation present on the site. Container seedlings have the impact of being grown in a restrictive container.

Numerous factors play a role in the development of root form once a tree seedling is planted out into the field besides the site conditions and soil properties. Factors such as stock type and planting technique can create serious deformities in the root systems of planted trees. These deformities may limit the uptake of water and nutrients, the production of photosynthates, and reduce stability or anchorage (Sutton, 1978).

The previous study outlined the poor Sr uptake in jP trees regardless of treatment and subsoil material. There are many possibilities that might explain the observations noted, but the one investigated in this study was that of root deformities. The root systems of 40 jP trees spread across four sites and two subsoil materials (overburden (OB) and tailings sand (TS)) were examined for root deformities and developed tap roots.

The null hypothesis was that root development of jP was not influenced by planting technique or reclamation material.

5.2 Material and Methods

All sites were located on reclaimed landscapes at the Syncrude Canada Limited (SCL) Mildred Lake Mine site, approximately 40 km north of Fort McMurray, Alberta, Canada. The mean annual temperature is 0.7°C with an average January temperature of -18.8°C and average July temperature of 16.8°C, based on climate data for the period 1971 to 2000 (Environment Canada, 2005). The mean annual precipitation is 455.5 mm with 342.2 and 155.8 mm as rainfall and snowfall, respectively.

5.2.1 Site Descriptions

This study was conducted at four jP sites, two on reclaimed OB and two on reclaimed TS. Two plantings were approximately 20 yr old and two about 10 yr old – one of each age on the different reclamation materials. The seedlings originally outplanted at the sites were grown in a greenhouse during the late winter/early spring for planting in August of that same year. The stock type varied and was noted for the individual sites where information was available.

5.2.1.1 S1 - 14 year old jP stand (S1-10)

The capping of the upper portion of S1 was done in 1987. About 70 cm of peat and secondary material were placed at this time. The site was not planted until 1990 when 22,000 jP seedlings were added by professional tree planters. The trees had been grown in Spencer-Lemaire containers (Super 45s, 750 mL containers). Due to problems with establishment, the site was underplanted in 2002 with trembling aspen (tA; *Populus tremuloides*) to a target density of 2000 stems ha^{-1}. At the time of this study, the site showed high vegetative competition from a thick understory composed primarily of grasses.

5.2.1.2 S1 - 24 year old jP stand (S1-20)

The lower part of S1 had undergone experimentation with fertilizer and seed (grasses and legumes) prior to 1980. The area received no mineral soil capping or only a few centimeters; in 1980, 7.5 cm of peat was applied to the lower part of S1. The construction material at this site consisted primarily of lean oil sands rather than the marine-clay shale typical of the newer OB sites (saline-sodic overburden; SSOB). Planting occurred directly into the material in 1980 at a high density (target of 5000 stems ha^{-1} trees and shrubs) to account for expected losses. The jP tree seedlings were grown in various Spencer-Lemaire containers (Hillson, Tinus, Five), styroblocks (4A, 7, 8, 20), and some paperpots. Observations at the time of this study indicated obvious water erosion events at the site and there was little understory vegetation present.

5.2.1.3 MLSB cell 6 – 12 year old jP stand

Capping of the Cell 6 TS area occurred in 1991 with direct placement of material to a targeted depth of 70 cm (nominal 50 cm not top dressed with peat). As a bench or level area between slopes, this site had only a slight gradation to the west. The site was planted with 3200 stems ha^{-1} in 1992. Seedlings were grown in 350 mL containers and planting was done by Athabasca Native Employment Corporation (ANECO). The understory at this site was of a typical jP stand dominated by kinnikinnick [*Arctostaphylos uva-ursi* (L.) Spreng.] and wild strawberry (*Fragaria* L.).

5.2.1.4 MLSB cell 18 – 22 year old jP stand

The Cell 18 TS area was capped in 1981 with 10 cm clay (from J pit) and 20 cm of peat. This muskeg was stripped from a gravel source, which allowed many large rocks or boulders to be carried with the peat material. Planting was done in 1982, and multiple species were used across the cell. In total, the target density was 4109 stems ha^{-1}, which included 16,115 jP over a 7 ha area, to yield a jP planting density around 2300 stems ha^{-1}. The stock type planted was a combination of small and large trees from Spencer-Lemaire Hillson and Tinus containers, respectively. The greenhouse crop for that year was 28,029 Hillson and 6200 Tinus; the number of individual stock type planted was not known.

Drifting and duning of TS occurred after this site was planted. Neither the date nor the duration of the duning was known; however, some of the trees were buried by over 1 m of TS. The deposited sand ranged from approximately 30 cm to around 140 cm above the original ground surface for excavated trees. The dominant understory species were grasses, with caragana present at the edges of the site.

5.2.2 Field Methods

A series of ten trees at relatively equal intervals were selected along a transect positioned diagonally down slope across each site. A diagonal sampling pattern was chosen to obtain examples that allowed for the slope variations in both the horizontal and vertical dimensions.

Laterally spreading surface tree roots were excavated manually using handtools (knives and spoons) in a radius of 50 cm around the base of the tree, unless the roots declined at angles requiring extensive removal of soil and such that the roots were no longer considered to be surface roots. At MLSB Cell 18, shovels were used to dig down through the duned sand to the original soil surface. All soil (and dune TS) was replaced around the roots after measurements were completed and recorded. The positions of laterally growing surface roots were sketched and their number and diameters at 50 cm from the tree base were recorded. If a taproot was present, its diameter (approximately 5 cm below the root collar) was also recorded. All laterally growing/spreading roots were measured. True laterals were often difficult to identify due to the kinking and coiling of the root system.

The extent of root deformity was recorded based on the procedures used by Bailey (2002) modified from Halter et al. (1993). Resemblance of the root system to the plug shape was also noted. However, instead of each true lateral root being measured and ranked for each deformity, all laterally growing roots were measured as mentioned previously, and the deformities ranked for the root system as a whole. To summarize the assessment method, a scale (0-9) was used to rank/define the degree of kinking and coiling observed. The extent of root kinking was determined by the quantity of 90 degree bends in a lateral root within 10 cm of the stem. Root coiling was judged by the extent to which a root encircled the stem (Bailey, 2002). A separate ranking was given for each deformity for the entire root system as opposed to each lateral root as done by Bailey (2002). A rating of 0 meant no deformities or that there were no kinks or bends within a 10 cm length of any root, or that roots did not circle the stem (Figure 5.1). Values of 9 indicated severe deformity with 2 or more bends in multiple lateral roots (10 cm from the stem) or that a root completely wrapped around the stem (Figure 5.1). Some of the root systems excavated and rated using this system can be found in Appendix H.

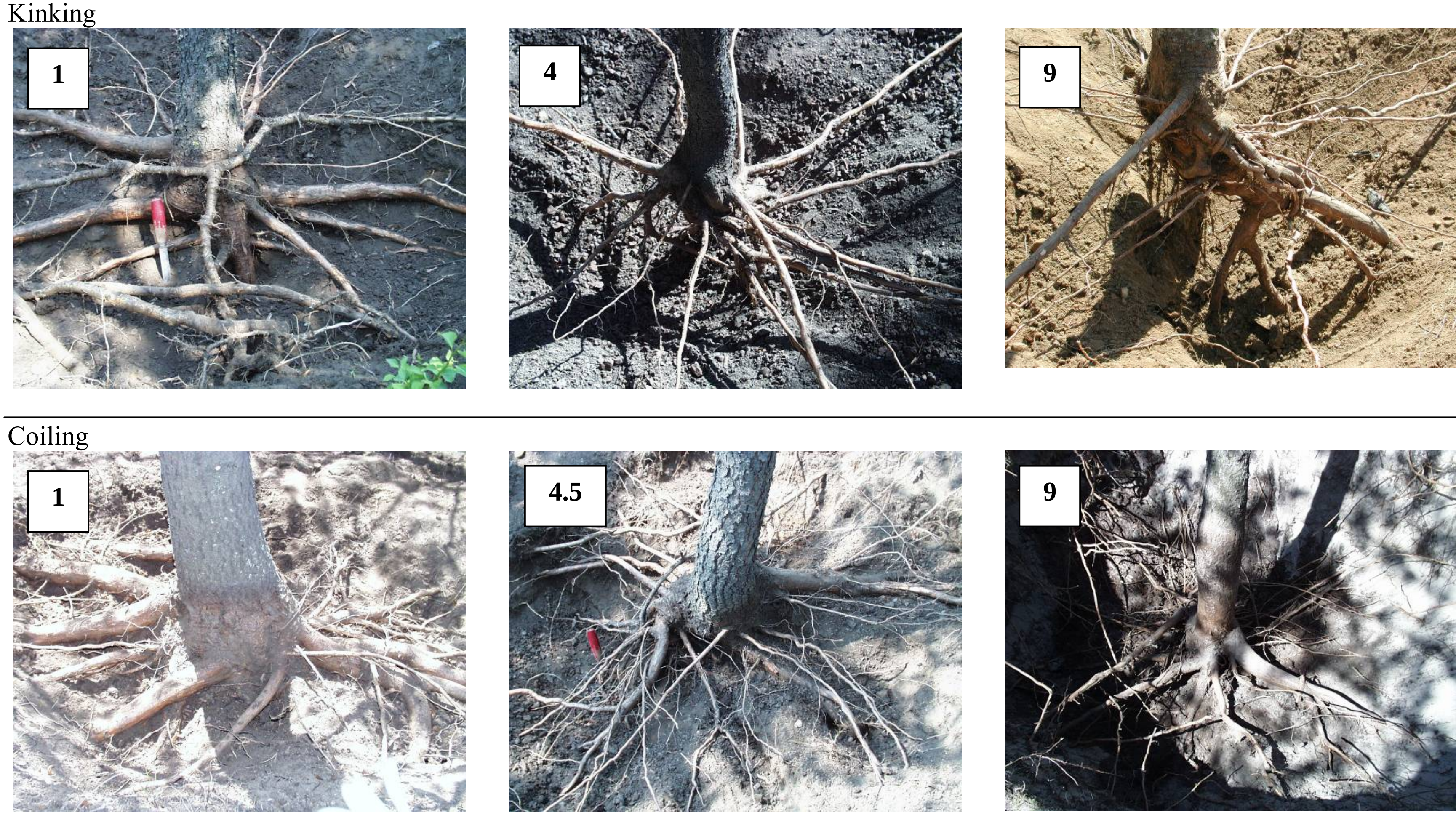


Figure 5.1. Examples of kinking and coiling ratings for excavated root systems using a scale of 0 to 9 (0 = no deformities; 9 = severe deformities).

5.2.3 Statistical Analysis

All statistical analyses were performed using SPSS version 13 and 14 (Chicago, Illinois). The number of laterals, number of laterals < 1 cm, diameter of laterals, and the diameter at the tree base were compared between TS and OB sites for the different age classes and comparisons between the age classes for the different construction materials using T-tests. The degree of kinking and coiling observed for the lateral root system was recorded on a relative scale, and as such, was evaluated using descriptive statistics to compare the medians for the ratings at each site.

5.3 Results

5.3.1 Lateral Roots

The mean number of lateral roots measured per tree (range 9 to 50) at each site and the average diameters (± 1 standard deviation, SD) of these laterals are presented in Table 5.1. There were slightly more laterally spreading roots per tree for the older sites versus the younger sites on their respective reclaimed materials; however, the difference was only significant ($p < .10$) for the TS sites. Additionally, a significantly higher number of roots occurred on TS versus OB for both of the respectively different aged sites ($p < .10$). The mean lateral root diameters (Table 5.1) for sites older than 10 yr (10+) (0.50 ± 0.39 and 0.45 ± 0.28 cm for S1-10 and Cell 6, respectively) were about half of the average diameters calculated for the plantings older than 20 yr (20+) (1.25 ± 1.06 and 0.99 ± 0.85 cm for S1-20 and MLSB Cell 18, respectively) and determined to be significantly different ($p < .001$). There was no difference in mean root diameters for the two reclaimed materials within the 10+ year old class, but at 20+ years old, the trees showed a significantly greater diameter on OB compared to TS ($p < .01$). Although the numbers of roots per tree were higher for the TS compared to the OB sites, the opposite trend was observed in terms of root diameter for the 20+ year old trees, where tree roots on TS had smaller diameters than those on OB. Trees on TS had more roots, but of a smaller diameter, while those trees growing on OB had fewer roots, but were of larger diameter.

There were numerous small diameter roots for trees of both the 10+ and 20+ year old sites; however, there were more roots for the younger sites and larger diameter roots

Table 5.1. Mean (± 1 SD) number of lateral surface roots per tree and average diameter of laterals according to diameter separation at a distance of 50 cm from the base of the tree.

Reclaimed material	Number of lateral roots per tree		Diameter of laterals	
	10+ year old	20+ year old	10+ year old	20+ year old
			------------- cm	-------------
		All roots		
TS	22.9 ± 3.5b†	31.6 ± 9.9a	0.45 ± 0.28c	0.99 ± 0.85b
OB	20.0 ± 5.2c	23.3 ± 6.2bc	0.50 ± 0.39c	1.25 ± 1.06a
		Only roots > 1 cm diameter		
TS	1.5 ± 2.0b	9.5 ± 4.5a	1.50 ± 0.46b	1.87 ± 0.99a
OB	1.0 ± 1.1b	9.7 ± 3.7a	1.32 ± 0.41b	1.86 ± 1.13a

† Different letters within a diameter class for each column and row are significantly different ($p < .10$).

for the older sites (Table 5.1). First order true lateral roots are typically of a larger diameter than other surface roots, but they were not specifically identified in this study. Assuming that a primary lateral root has a relatively large diameter, roots with diameters of > 1 cm were selected from the data and analyzed. The 10+ year old sites averaged 1.50 ± 2.0 and 1.0 ± 1.1 roots > 1 cm per tree for S1-10 and Cell 6, respectively, while the mean number of roots with diameters > 1 cm for the 20+ year old sites were 9.7 ± 3.7 and 9.5 ± 4.5 for S1-20 and Cell 18, respectively (Table 5.1). Both the number and diameters of roots > 1 cm were significantly higher for the 20+ year old sites as compared to the 10+ year old sites on both TS and OB. There were no differences in root number or diameter between the TS and OB sites, regardless of age class.

Not all trees had lateral roots > 1 cm diameter. Table 5.2 summarizes the percentages of trees at each site with roots in the different diameter classes. Only 1 in 2 trees at S1-10 had roots in the 1 to 2 cm diameter class and only 1 in 5 trees had lateral roots with diameters of 2 to 3 cm. All excavated trees at the older sites (100%) had lateral roots in the 1 to 2 cm diameter class. Neither of the younger sites had any lateral roots with diameters ≥ 3 cm, while older sites had 20 to 30% of trees with roots in the 5 to 6 cm diameter class. As anticipated, the older trees had a greater proportion of roots with larger diameters. No trees had roots > 7 cm in diameter at 50 cm from the stem base.

The highest median value for root kinking was determined at the S1-10 site where seven of the ten trees rated a 9 indicating an extreme deformity (Figure 5.2). The remaining three root systems had little to no kinking. Root coiling was not as severe, but S1-10 still ranked the highest of all sites with a median value of 6. The three other sites had median values below 4 for kinking and coiling roots. The median kinking ratings of root systems in the 20+ year old sites were 3.8 and 4, while median coiling ratings were 3.8 and 3 for S1-20 and MLSB Cell 18, respectively. The median kinking and coiling ratings for root system in MLSB Cell 6 were 4 and 2.5, respectively. Refer to Appendix H for photographs of a range of deformed root systems based on kinking and coiling. The resemblance of the root system to its plug shape/form when planted was not rated, but was observed to be greatest at S1-10 and to a lesser extent at MLSB Cell 18, although some trees showed good lateral spread.

Table 5.2. Percentage of trees with laterally spreading roots in different diameter classes measured at 50 cm from the stem for each site (n=10).

Reclaimed material	Age	Site	Lateral Root Diameter Classes (cm)					
			1-2	2-3	3-4	4-5	5-6	6-7
			------------------------------ % ------------------------------					
TS	10+	Cell 6	60	10	0	0	0	0
TS	20+	Cell 18	100	80	30	20	30	0
OB	10+	S1-10	50	20	0	0	0	0
OB	20+	S1-20	100	70	60	50	20	10

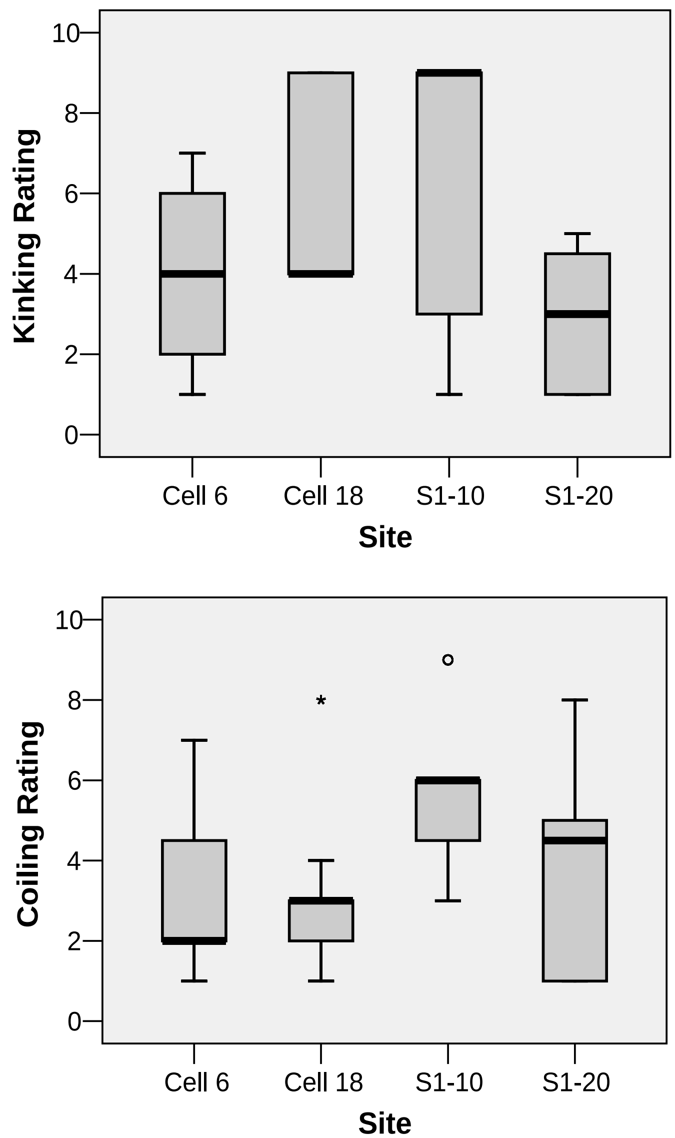


Figure 5.2. Box plots of kinking and coiling values for root systems of trees at each reclaimed site (n=10). The black horizontal line within the box indicates the median rating

5.3.2 Taproots

For all sites, 28 out of 40 jack pine trees had not developed taproots. The decreased taproot development coincided with the trees that had the greatest plug resemblance. No trees at S1-10 developed a taproot. At Cell 18, S1-20, and Cell 6, 3, 4, and 5 out of the 10 excavated trees, respectively at each site had taproots (Table 5.3). The largest mean taproot diameter (where a taproot was present) was measured (~ 5 cm below the root collar) at S1-20 (4.5 ± 1.2 cm) followed by Cell 18 (3.7 ± 2.1 cm) and Cell 6 (3.5 ± 0.6 cm).

The mean stem diameters measured just above the root collars were not statistically different between subsoil materials (TS and OB) within either the 20+ year old sites or the 10+ year old sites. Stem diameters were significantly different ($p < .001$) between the two age groups on both TS and OB sites, with the 20+ year old trees at about double (14 cm) the diameter of the 10 + year old sites (7 cm) (Table 5.3).

5.4 Discussion

A higher number of lateral roots were found on older than younger trees and significantly more for those older trees growing on TS compared to OB sites. Stein (1978) and Grene (1978) noted that planted tree root systems had more fibrous root mass clustered near the taproot (a denser less open system). Conversely, Halter et al. (1993) found lodgepole pine to have fewer lateral roots on planted versus naturally regenerated trees (14 compared to 25, respectively), as did Harrington et al. (1989) for loblolly pine. Roots also were smaller on planted trees (Harrington et al., 1989). Lodgepole pine had between 12 and 20 laterals per tree with mean diameter of 2.9 to 6.5 mm (Van Eerden, 1978). Lindström and Rune (1999) found no significant difference in the number of roots on Scots pine between planted and naturally regenerated young (14 years) and old (22 years) trees. Sundström and Keane (1999) found 21 roots at 15 and 30 cm from the stem and this number decreased at 60 cm from the stem. Van Eerden (1978) found lateral roots of trees on fine textured moist soils to be more numerous and bigger than on coarser drier sites. As cover soil prescription of the reclaimed sites were similar for the two 10+ year old sites, their differences in lateral root numbers were more likely a factor of stock type and planting technique than soil texture. Van Eerden (1978) also reported that

Table 5.3. Percentage of trees with taproots and mean (± 1 SD) stem and taproot diameters (n=10).

Site	Percent of Trees with Taproots	Mean Stem Diameter†	Mean Taproot Diameter ‡
	%	---------------------- cm	----------------------
Cell 6	50	7.2 ± 1.0	3.5 ± 0.6
Cell 18	30	14.3 ± 3.4	3.7 ± 2.1
S1-10	0	7.1 ± 2.1§	--
S1-20	40	13.8 ± 4.1	4.5 ± 1.2

† Tree stem diameter was measured above root collar.
‡ Measured ~ 5 cm below root collar
§ For this measurement and site, n=9.

lateral distribution was variable and the configuration reflected the container type and species characteristics.

Although not measured or ranked, asymmetric root systems (those root systems with unevenly distributed root systems) occurred at several sites (Figure 5.3). The observed was only noted qualitatively and was not quantified in any way. Three of the four sites were sloped and some asymmetry of the root systems was expected. At MLSB Cell 18, it is believed that the original shallow cover soil and number of large rocks resulted in the seedlings being planted at an angle in the soil cover. Lateral root growth was promoted in approximately half the circle excavated and contributed to some of the kinking. Both slope and stoniness increased the asymmetry of root systems with more rooting usually occurring on the downhill side, although root development also extended uphill and along the contours (Eis, 1978). For Cell 18, asymmetric growth appeared upward, with most of the rooting occurring towards the top of the slope into the direction of the duning. At S1-10 and S1-20 there was a greater slope gradient and more roots seemed to occur downslope, while large diameter laterals also extended along the contours.

Taproots had not developed for the majority of jP trees excavated, similar to other research on planted pine trees. Segaran et al. (1978a; 1978b), Hellum (1978), and Long (1978) all recorded poor to no taproot development 6 to 8 years after planting for jP, wS, and multiple conifers (Douglas fir, Western hemlock, noble fir, ponderosa pine, and lodgepole pine), respectively. Hay and Woods (1974; 1978) found that deformed root systems (J, double J, knotted) of loblolly pine had no original taproot, but significant lateral root development and some laterals often took over and acted as taproots. This lateral root functional adjustment was observed on some of the reclaimed sites; for a few trees where no taproot had formed, some laterals descended rapidly in an oblique direction and took over for the missing taproots. As previously mentioned, at MLSB Cell 18 the large number and size of rocks may have contributed to taproot restriction; however, the extreme deformities suggest that the planting and stock type were likely the primary factor in poor root development at this site.

The influence of stock type on root deformities, however, could not be determined from this study because more than one container type was used to grow the

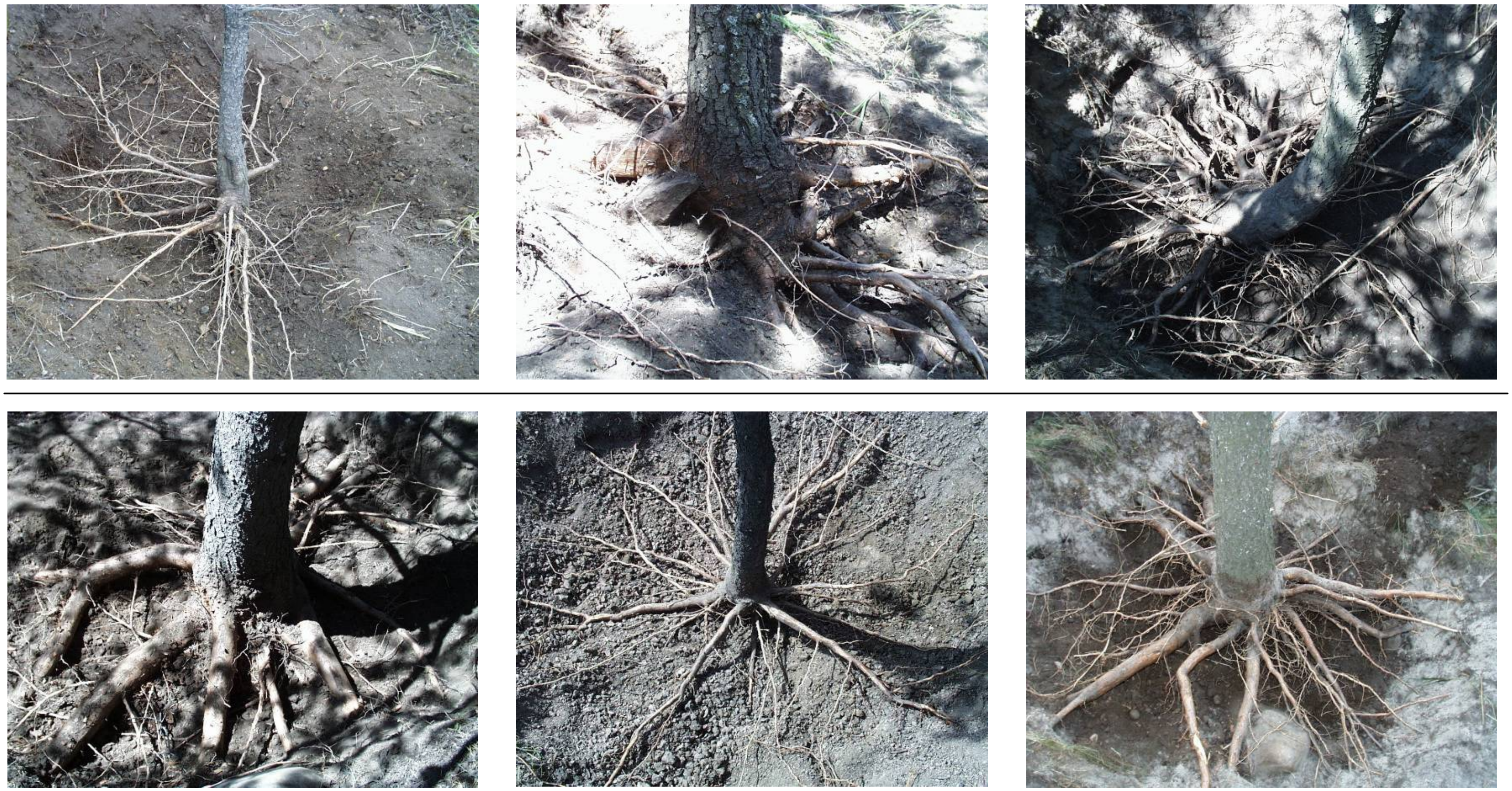


Figure 5.3. Photos of root systems with apparent asymmetry (top) and more symmetric root systems (bottom).

tree seedlings which were planted at three out of the four reclaimed sites. Also more than one stock type was used at individual sites and excavated trees could not be identified as to which container stock they originated from. Only MLSB Cell 6 had a single planting stock type used for the entire site. Previous research has shown the influence of stock type/container type on both shoots and roots of trees. Segaran et al. (1978a; 1978b) reported that from 3 to 6 years after planting, naturally regenerated jP trees had greater height growth than bareroot or container stock. During years 4 and 5 after planting, but not in year 6, bareroot seedlings had greater height growth than containerized stock (Segaran et al., 1978a; 1978b). Root collar diameter (RCD) and dry mass of jP trees were affected by stock type while there was little effect on height four and six mo. after planting in studies by Girouard (1982). After three years, Carlson and Nairn (1977) reported significant differences in height and RCD. Container effects on roots were noted to begin only 8 wk after seeding jP (Carlson and Nairn, 1977). Most seedlings had some kinked roots, but coiling and compression were the most pronounced for the BC/CFS Styro 2 (no ribs) and the 408 paperpot three years after planting. Long (1978), Van Eerden (1978), and Girouard (1982) found that root coiling was not only affected by container, but also was species influenced, generally with pine being more spiraled. Cultural practices can affect symmetry, balance, constriction, and coiling of root systems, as well as taproot development and the extent of root deformation at planting (Long, 1978).

It was thought that soil compaction might be an issue for tree establishment and root growth, but testing with a recording cone penetrometer (Eijkelkamp, Netherlands) with a base surface cone of 1 cm^2 (data not shown) showed no problems with soil resistance in the upper 50 cm of cover soil at S1-10. Although soil resistance was not a problem, it did not mean that root growth could not be impeded or restricted in some other way. Examination of root systems showed intensive kinking and coiling for 70% of the excavated trees which could reduce stand productivity. Root systems at S1-10 showed greater plug resemblance than at other sites (Figure 5.4). Additionally, the understory vegetation at this site was extremely aggressive and healthy. Some of the grasses were ~ 1 m tall and a thick sod layer had to be dug through to find the tree roots when excavating. Jack pine, wS and white pine can suffer decreases in height and

Figure 5.4. Photos of excavated jack pine showing tangled root systems and plug resemblance.

diameter growth with herbaceous vegetation competition (Noland et al., 2001) resulting in increased height:diameter ratios and stem volume (60-79%). The best growth in the presence of competition was measured for seedlings with the largest RCD (Noland et al., 2001). It is most likely that the poor jP growth and survival observed at the S1-10 site was in part due to intense herbaceous vegetation competition in addition to poor planting techniques where seedling root systems were coiled or balled up.

Typical pine trees have a well-developed taproot with a system of lateral roots. First order lateral roots come from the primary taproot and orient horizontally with an even or symmetrical distribution around the stem (Lindström and Rune, 1999; Rudolph and Laidly, 1990; Burdett et al., 1986). Planted trees will have a different root form than naturally regenerated trees; however, seedlings with root systems as close to the natural system as possible are desired. Containers that promote downward growth of roots and permit root pruning (chemical, air, or mechanical) help to achieve better structural and stable seedling root forms (Chapman and Colombo, 2006) which can rapidly grow laterals and taproots (Chavasse, 1978). Good site/soil conditions also aid in seedling establishment and stability. In shallow or stony soils, tree roots may be restricted and affect the anchorage of the tree (Elie and Ruel, 2005); thus, trees at MLSB Cell 18 may be at a site disadvantage due to the stoniness of the subsoil material. For a pine tree seedling, taproots develop first, elongating for two to three years. Obstructions like rocks stop growth if they are perpendicular, creating a branch above the obstruction where growth occurs steeply oblique or the branch may grow along rock surfaces if the angle was not perpendicular, leaving the laterals and oblique roots to take over the support for the tree (Eis, 1978). At S1-20, the soil resistance may be influencing rooting as the penetrometer would not pass through the near surface reclamation material (i.e., the resistance exceeded 5 MPa within 10 cm and could not be measured) in the few locations selected. In some of the excavations, the lean oil sands were observed to be like asphalt around the roots and yet above ground, the trees appeared to be doing better than the trees on the younger (S1-10) site where soil resistance was not an issue. Measurements for soil resistance taken at MLSB Cell 6 showed no resistance problems, although measurements were slightly higher than at S1-10 at depth (data not shown). The older sites showed greater rooting restrictions and potential anchorage problems. However, for some trees at

S1-20, the roots were nearly cemented into lean oil sands, suggesting good strong root to soil bonds – one factor in tree anchorage (Stokes, 2002).

Root grafting at the base of the tree was excessive (Figure 5.5) on the older sites making kinking/coiling measurements difficult. Only visual ratings were used todetermine kinking and coiling; however, cross-sections of the root base would likely show greater kinking and coiling as they would not be hidden by grafting. Root grafting occurs when two or more roots are in contact with increasing pressures from diameter growth, leading to eventual breakage of the bark and fusing of the cambium layers, thus creating the appearance of one root (Hagner, 1978). Segaran et al. (1978a; 1978b) reported significantly higher root grafting for bareroot versus naturally regenerated trees and the number of grafted roots increased with age. Hagner (1978) examined 50 yr old pine plantations (all species not identified, but did include *Pinus sylvestris*) and reported that initially as the root clump fuses into a mass there may be some instability, but later secondary roots form in proper orientation. Girouard (1982) mentioned that when roots spiral and graft they restrict natural root development and may be more susceptible to armillaria root rot decreasing their competitive ability and reducing tree stability.

Kinking and coiling of the root systems were rated based on the whole root system which provides less information about each lateral, but still provides a simple visual scale of the deformities occurring throughout the plantings. The final form of a root system is determined early with the first roots being structural; the shape, size, and symmetry of root systems depends on the number, growth, and branching of first roots (Eis, 1978). Roots can become kinked or spiraled around inside a container when grown in the greenhouse or nursery (Carlson and Nairn, 1977; Girouard, 1982) and can persist in seedling root systems even after outplanting (Grene (1978). Continued research into containers and options for root pruning has developed slotted containers/root trainers (Long, 1978) that train roots to grow downward instead of spiraling and can be combined with chemical, air, or mechanical root pruning methods which promote rapidly growing laterals and taproots (Chapman and Colombo, 2006; Chavasse, 1978). Proper container selection and continuing monitoring is needed to evaluate how root systems develop after outplanting. However, even if the planting stock and root system development in containers is of high quality, poor planting techniques can contribute to root deformities,

Figure 5.5. Photos showing root grafting of excavated jack pine root systems at 10+ (top) and 20+ (bottom) year old trees.

especially L- or J-shaped root systems, poor taproot development, and balled-up root systems (Segaran et al., 1978a 1978b).

Although root strangulation/coiling can impair tree growth, it usually does not kill the tree. However, stability decreases with increasing root deformities (Grene, 1978; Burdett, 1978) making trees more susceptible to toppling and windthrow (Burdett, 1978; Hellum, 1978). With root spiraling, there can be a proliferation of weak lateral roots at the base which do not firmly anchor the tree (Van Eerden, 1978). Although Hagner (1978) suggests that root grafting and secondary root growth can stabilize trees, Grene (1978) commented on how these deformities may just be deferred until later when uninhibited top growth exceeds the poor root growth late in a tree's life. Bell (1978) reported that root coiling of *Pinus caribea* in containers remained after outplanting and was related to stem breakage at ground level. Scots pine root system structural abnormalities were apparent 19 to 21 years after planting (Lindström and Rune, 1999). Although it may be difficult to see root deformities on the exterior of a root system after grafting has occurred, inside of stumps the bark remains creating fiber disturbances which lower the tensile strength of the wood compared to naturally regenerated trees. For reclaimed sites where root grafting is observed, the trees are likely to be weaker and less stable until a good secondary root system develops. In addition to problems with stability, root systems that are J-shaped or knotted have restricted carbohydrate flow, creating an accumulation zone above the deformity usually defined by swelling (Hay and Woods, 1974; 1978). The reduced carbohydrate flow, necessary for root growth, can affect root development.

Besides influences from cultural or nursery practices and planting techniques, the site itself can impact root form and development. Pines were more affected by soil conditions than spruces and suffered from decreased resistance to uprooting on shallow or stony soils (Elie and Ruel, 2005). In terms of productivity, Béland and Bergeron (1996) suggest that the low nutrient requirements of jP and solid taproot make soil depth and bulk density more important factors than nutrient status (richness). Paterson and Maki (1994) found seedling survival to significantly decrease with poor microsite selection, but no significant differences were observed for planting depths. Chrosciewicz (1963) examined the effect of site on jP and determined soil moisture, texture, petrography, and regional macroclimate all influence site indices. The addition of soil by Coutts and Nicoll (1991) to the planting surface after germination of conifers resulted in further upward growth of laterals. At MLSB Cell 18, roots were observed growing upward toward the soil surface through the duned sand. The weight of the sand may have also acted as a stabilizer for some of trees. One tree did fall over after the duned TS was removed and the tree was left overnight with the original soil surface exposed in an approximately 50 cm radius from the stem. The root system of this tree was extremely kinked and there was no taproot development.

Taproots are important structural components of jP tree anchorage. It is typically the first part of the root system to develop and is maintained through to maturity (Rudolph and Laidly, 1990). Dupuy et al. (2005) reported that both soil and rooting habit influenced resistance to uprooting. With planting, structural root anomalies can occur including poor root system symmetry, root deformities (coiling, kinking, and constriction), poor development of sinker roots for stability, disproportioned lateral roots, and basal sweep and/or toppling (Halter et al., 1993). Sundström and Keane (1999) found every second bareroot seedling and every third container seedling to have basal sweep [bending of the stem near the base of the tree which usually straightens later in the trees life with compression wood (Sundström and Keane, 1999)]. There were some planted trees at all reclaimed sites which had large bends at the stem base (Figure 5.6). Given the extent of root deformities on the reclaimed sites, knowledge of the reduced stability of trees with deformed root systems, and awareness of some stem curvature, leads us to believe that a small proportion of trees may be lost at some time in the future to toppling or windthrow. The forest stands that were planted on the S1 sites in their current states would be challenging to reestablish. Reestablishment on the MLSB sites would likely be easier and some new conifer seedlings (spp undetermined) were germinating under the jP stand on the duned sand at Cell 18.

5.5 Conclusions

More attention to the planting program and planting technique would help to ensure proper root system development of trees. Incorrect planting techniques have resulted in poor taproot form for 70% of the jP trees examined in this study. Proper

Figure 5.6. Photos showing stem bending for 10+ (top) and 20+ year old trees (bottom).

planting of seedlings has been an issue in forest regeneration for decades and the increased potential for toppling and windthrow of affected trees is well documented.

The jP root systems often showed planting deformities such as kinking and coiling in addition to poor taproot development. These root deformities have likely exacerbated the effects of herbaceous vegetation competition for S1-10. Where environmental conditions or stresses exist, the effects from deformed root systems are more likely to be magnified. The influence of site, for example, the stoniness at MLSB Cell 18 can further restrict root system development. Judging by the asymmetries observed at this site, it is suspected the seedlings were planted at angles to ensure root systems were covered. Improper planting limited the root systems, as did the restriction from numerous rocks.

More lateral roots were recorded for the older sites; it is believed these were partially secondary lateral roots, but more often this increase in measured roots was likely due to branching of the primary root system. The root systems of planted jP on reclaimed oil sand sites, whether TS or OB, had centrally dense root systems influenced from their original stock root form as opposed to more open seeded or naturally regenerated root systems.

6 GENERAL DISCUSSION AND CONCLUSIONS

Reclaimed landscapes, such as those designed by Syncrude Canada Ltd. (SCL), are intended to return the land to a productive capability equivalent to that which existed prior to disturbance, supporting commercial forest and wildlife habitats. The goal is to achieve functioning ecosystems on the landscape which will mature naturally, maintenance-free, and be self-sustaining, offering no major risks to plants or animals that are either resident or migratory (OSVRC, 1998). Soil reconstruction is critical as vegetation is dependent on the soil and its properties. Unlike machines, soils and landscapes cannot be taken apart and put back together to either look or function exactly as they once did. However, they are reconstructed in such a way as to meet as many environmental, physical, and chemical requirements as necessary for the proposed new landscape features and desired ecosites, planting them with the appropriate vegetation.

In the reclamation of saline-sodic overburden (SSOB), typically a 1 m mineral soil and/or peat layer (cover soil or capping) is placed on top of the SSOB to provide for the growth of new forest ecosystems. This soil cover needs to provide adequate moisture, nutrients, rooting depth, and structural anchorage for the trees to survive and sustain themselves. The overburden material is highly saline and sodic, has a low hydraulic conductivity, elevated pH, and high clay content. This material has been relocated from many meters below ground to near the soil surface, placing tree roots in close proximity to an unfavorable growing environment. This research attempted to shed light on the questions of whether or not the physical and/or chemical conditions of the cover soil and upper SSOB were influencing root growth (and subsequent tree growth) of the forests within the reclaimed area and if planted trees showed any root deformities that might limit their potential growth.

For the first part of this study, root distributions on reclaimed saline-sodic overburden were examined to determine if the planted trees were impacted by the salts and/or sodium from the SSOB that now was closer to the tree roots. For all sites, root densities were highest in the upper 30 cm of the soil decreasing rapidly with depth and fine roots dominated the soil profiles. Despite their young age, the sites all showed root distribution patterns typical of boreal forests, although the amount of rooting and extent to which the roots explored the soil profile was limited. In terms of a forest rotation, these sites are very young and it was probable that the understory vegetation made up a large proportion of the total root density measured at the sites; however, the amounts attributable to each species were not determined with the root sampling in this study. Future root measurements may tell a different story. As the trees begin to explore more of the soil profile, as the soil structure develops, and salt and water movement adjust to a new equilibrium these could all impact root development as the landscape matures.

The EC and SAR profiles for the same soils showed a reverse pattern to that of the rooting distributions, where at SW30 and S2, the EC and SAR increased with depth as opposed to the root densities which decreased with depth. The increases in salinity and sodicity with depth were due to the upward diffusion of salts and sodium from the interface layer into the cover soil. This new salt and sodium gradient could potentially influence tree root distributions as the EC and SAR values were in the range which would affect plant growth. Soil depth, Na and EC had significant negative relationships with root length density at each reclaimed site, suggesting that the roots do not grow well with increased salt or sodium; however, depth was highly correlated (whether negatively or positively) with every variable thus making the inferences of these variables on roots more difficult to decipher. It is clear that the negative correlation of depth with the soluble cations, EC, and SAR is in part due to the anthropogenic reconstruction of the soils and the pedogenic processes that have begun to take place. Another factor not measured in this study that relates further to the varied thickness of cover observed for the sites and slope position, is soil moisture – also critical to tree growth. Further investigation into the influence of cover thickness, soil moisture, texture, and slope influences on rooting and salt movement would provide a clearer indication of the cover soil's chemical and physical influences on tree rooting with age.

From the root distribution study in Chapter 3, we did not know if the trees were rooting to depths that would cause them to be impacted by the increased salinity, although we did discover that a small proportion of roots were growing in the SSOB material below the cover. The root activity (strontium) study (Chapter 4) was used to investigate which species were responsible for the root growth into the SSOB. The results were not as straightforward and conclusive as hoped. The only significant increase in foliar Sr concentrations compared to the control was seen for the jP on TS in the fall, only two months after the application of $SrCl_2$. The wS showed no significant increase in foliar Sr concentrations over the control, suggesting that there was no active root growth at depth or at the surface. This was not a probable outcome given the previous study which showed the majority of rooting occurred in the upper 30 cm of the soil. It was suspected that the understory offered a lot of competition for the added Sr or the roots were so deformed or asymmetrical they were unable to access the tracer. The amount of tracer applied also may not have been sufficient to be detected in the trees as the trees may have diluted the Sr throughout their growing tissues to undetectable levels compared to the control. These issues could have been somewhat abated by using higher treatment rates of $SrCl_2$ and multiple sampling times. Strontium concentrations in jP tissue were extremely low regardless of treatment, sampling time, or site. Although jP has a low Ca requirement, it has been shown to respond with increased Sr concentration in greenhouse experiments (Franklin et al., 2002). The levels of foliar Sr for the understory species suggested that there was indeed competition for the Sr, particularly the surface broadcast treatments and helped identify what might be high Ca requirement species. The increased Sr content for clover, grasses, and sow thistle in the depth treatments suggest that these deep-rooted understory species might be the source of roots in the SSOB, especially with clover's higher salt tolerance.

If the species rooting deepest into the reclaimed soil profiles and into the SSOB material were the understory species, it would have a large impact on the rooting distributions as the forest ages, the canopy closes, and less of these species are present. The proportion of roots that these understory species represent at different depths is unknown. The greater rooting depth of understory species could mask tree rooting problems. They contribute a great deal in developing root channels to greater depths which will affect the water and salt transport systems, the distribution of organic matter, and the developing structure of the cover soil. Further investigation into the rooting profiles of individual species on reclaimed sites would contribute to a better understanding of the salinity and sodicity influences on the forested areas. The current data suggests that the ecosystems would not be negatively influenced by the salinity and sodicity that exists at depth and that forest ecosystems similar to naturally saline forests would develop.

Investigation into the lateral and taproot development of excavated jP root systems found common planting deformities on all sites. The kinking and coiling of roots and poor taproot development resulting from improper planting have been a concern for decades to forest companies and despite the research and information available, it continues to be a problem at plantations everywhere. Jack pine trees require both a good taproot and lateral root system to have adequate anchorage in the soil, although the exact form of the root system is partially dependent on properties such as soil texture or obstacles which may limit typical root growth. Toppling and windthrow, especially during high wind events, may be a concern for several plantations on reclaimed sites as the trees mature and growth of the above-ground portion of the tree exceeds the ability of the root system to support it.

Although the reconstructed soils consist of salvaged peat, mineral soil, and OB present at the site prior to mining, reconstruction creates an artificial profile with abrupt changes between these materials and new gradients need to develop. These new gradients or equilibriums may include the hydro- and hydrogeological cycle, nutrient or solute cycles, vegetation succession patterns, and the establishment of plant, animal, insect, and microorganism communities. Over time, the actual equilibriums achieved may differ somewhat from the desired or anticipated landscape system, but that does not mean it would not be functioning or sustainable, but that the end result may be different from what was expected. Eventually, the reconstructed soil profiles will begin to undergo horizon development and forest floors will start to accumulate, but it will take time. The success or sustainability of reclaimed forest ecosystems cannot be judged only from what is visible at the surface. It also cannot be determined from examinations of young sites alone. Monitoring of forest progress and productivity, i.e., its growth both above- and below-ground as well as any successional occurrences, should be monitored over a longer period of time.

This research demonstrated the importance of proper planting techniques and suggested that improved planting would benefit the belowground health and subsequent aboveground productivity of the reclaimed forested areas. However, the current root density distributions were typical for boreal forest ecosystems and the salinity and sodicity profiles did not appear to pose a problem for the development of functioning forest ecosystems. It is likely that forests on the SSOB will develop in much the same manner as the naturally deep-saline forests in Alberta, provided the salts do not continue to migrate into the soil covers. Volunteer tree and shrub species were observed at all of the reclaimed sites, and newly emerged conifers were noted for one of the sites. In terms of ecosystem sustainability, this suggests not only that viable seed or reproductive sources exist in the cover material, but that natural regeneration on at least some of the reclaimed sites is possible and may already be occurring.

In March 2008, Syncrude Canada Ltd. gained their first reclamation certification for Gateway Hill (SCL, 2008). This certification acknowledges the return of the land to a forest capability equal to or greater than what existed prior to disturbance. For reclaimed sites intended for commercial forestry, standards in regards to adequate volumes of accepted species also must be met. It is this author's belief that the reforested-reconstructed landscapes at Syncrude's Mildred Lake mine site are continuing to adapt and change as the various aspects of the forest ecosystems interact (whether physical, chemical, or biological) to achieve a new balance, but the time frame that this may take to occur is not fully understood. Future research into the influences of soil moisture on root distributions, the true extent of the tree rooting zones, and the role of the understory species on water balance and plant salt tolerances will provide further insight into this new dynamic system. Although typical rooting distributions were found for this snapshot in time, it will be important to monitor the effects of the interface layer and the SSOB on continued tree root development.

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APPENDIX A: WEATHER DATA FOR FORT MCMURRAY AND SYNCRUDE CANADA LTD. MINE SITE

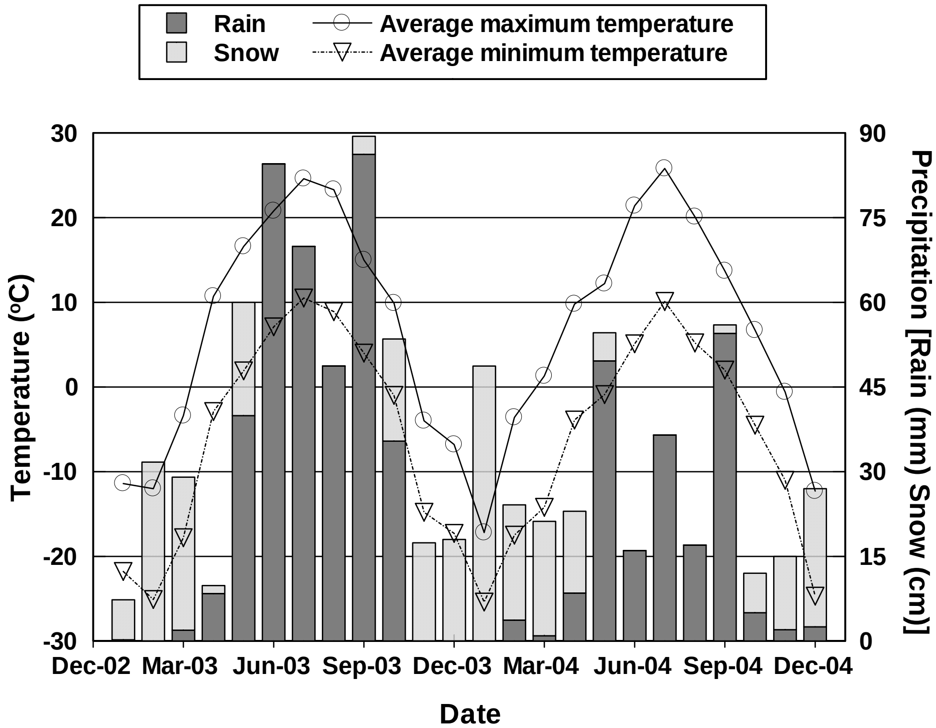


Figure A.1. Environment Canada weather data recorded at Fort McMurray airport for 2003 and 2004 (Environment Canada, 2005).

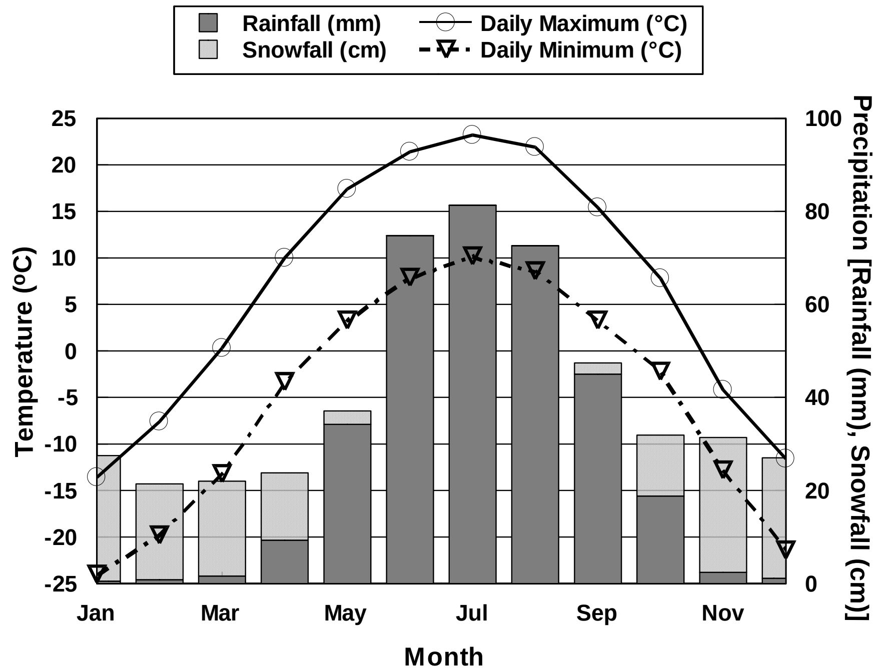


Figure A.2. Environment Canada average daily temperatures and average monthly precipitation for Fort McMurray, Alberta based on data from 1971-2000 (Environment Canada, 2005).

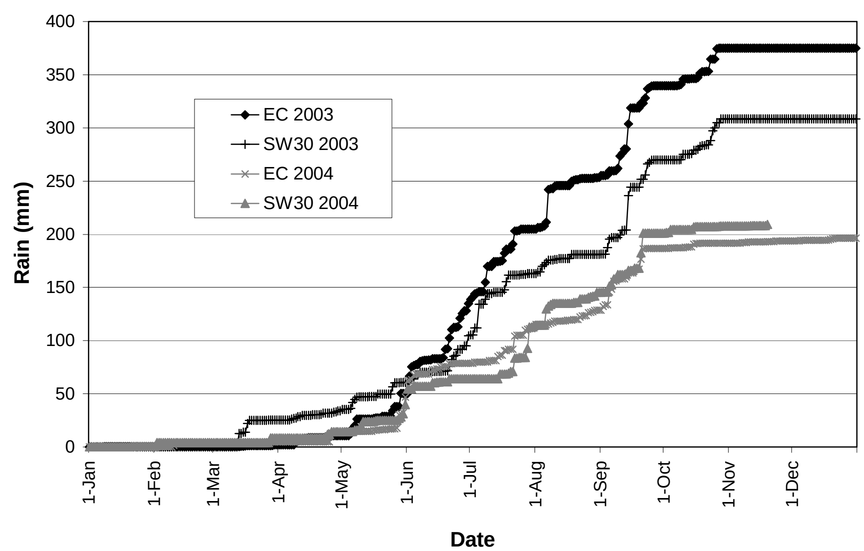


Figure A.3. Cumulative rainfall collected on SW30 and Fort McMurray (EC) airport. Data for SW30 provided by O'Kane Consultants Inc. and Climate data for Fort McMurray airport obtained from Environment Canada (2005).

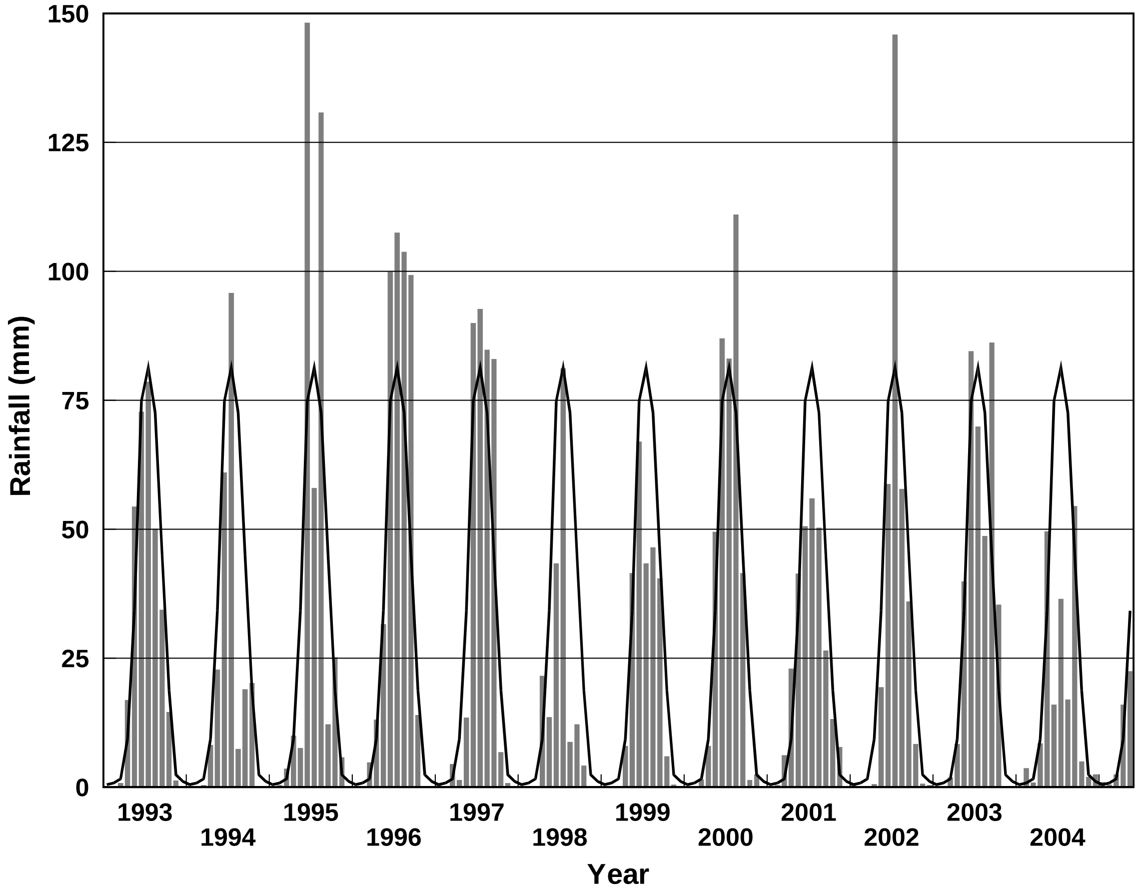


Figure A.4. Monthly rainfall amounts measured at Fort McMurray, AB airport (column) as compared to 30 yr monthly average rainfall (line) from 1971-2000 (Environment Canada, 2005).

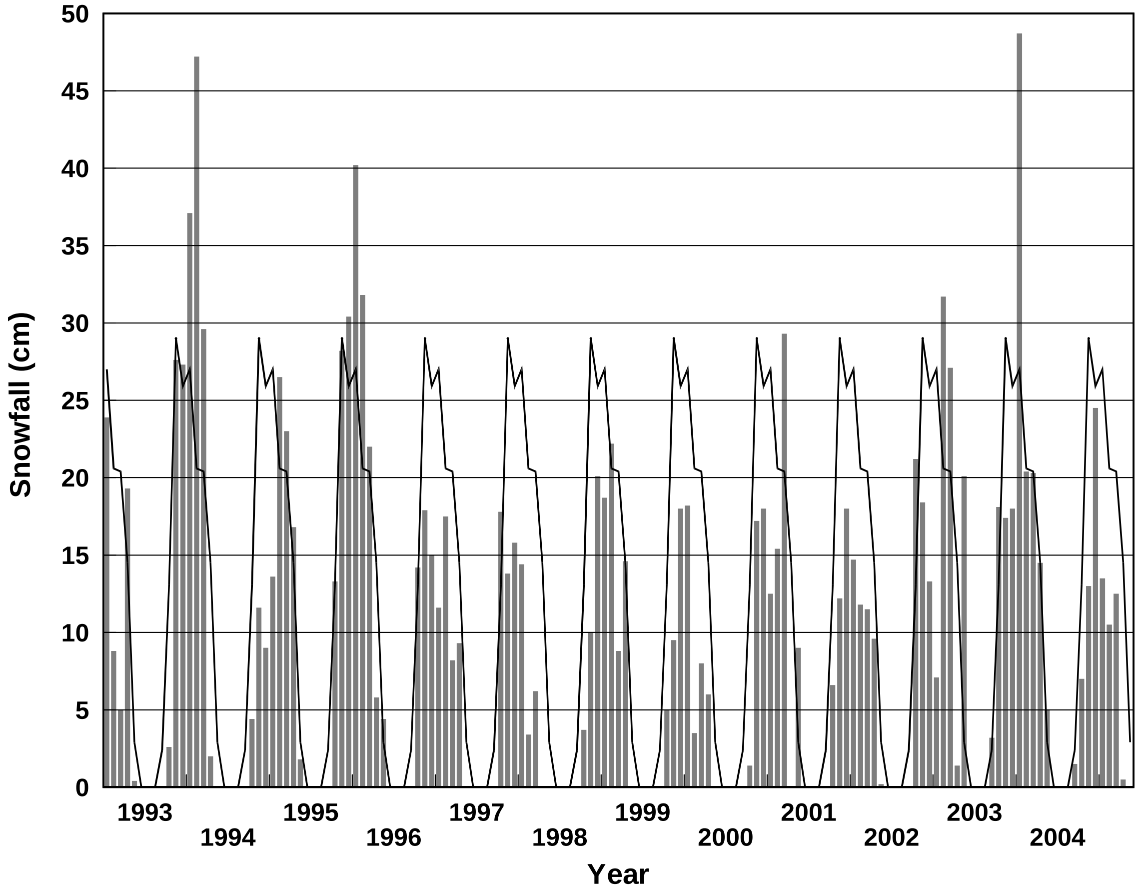


Figure A.5. Monthly snowfall amounts measured at Fort McMurray, AB airport (column) as compared to 30 yr monthly average snowfall (line) from 1971-2000 (Environment Canada, 2005).

APPENDIX B: SITE MAPS, BACKGROUND INFORMATION, SAMPLING DESIGNS, AND GPS LOCATIONS

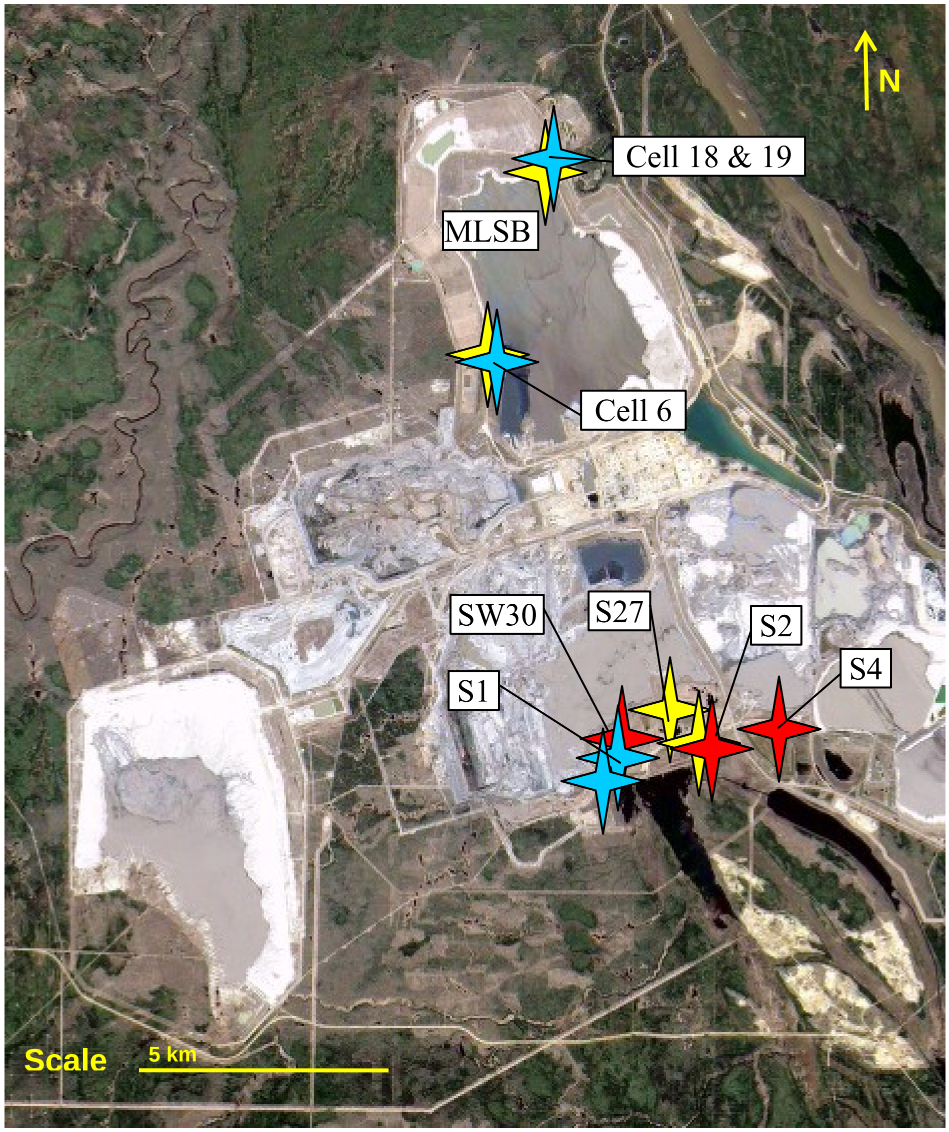


Figure B.1. Satellite imagery (SCL, 2003) of Syncrude Canada Limited Mildred Lake mine site showing the relative locations of reclaimed sites used for the studies conducted in Chapter 3 (red stars), Chapter 4 (yellow stars), and Chapter 5 (blue stars).

Table B.1. Capping and planting details for reclaimed sites used in each research study (Chapters 3 to 5).

Site	Capped	Planted	Capping Material	Planting Density	Container type	Other
MLSB Cell 5/6 step-out	1991	1992	under 70 cm DP (nominal 50 cm; not top dressed with muskeg)	3200 stems ha^{-1}	350 ml containers	Planted by Athabasca Native Employment Corporation (ANECO)
MLSB Cell 18	1981	1982	10 cm clay (from J pit), 20 cm muskeg (muskeg stripped from a gravel source) – report 20-22cm peat, 10-13 cm clay (ph 7.5, OM 6.8, S:Si:Cl = 30:27:43%	4109 stems ha^{-1} but multiple species: 7 ha using 16115 jP	28029 Small Hillson 6200 large size trees – probably Tinus (some of each planted)	
MLSB Cell 19	1994	1994	50 cm mineral (from NW quad), 20 cm muskeg (NT-2 stockpile) or 70 cm direct placement (NW quad)	No information available		
S2 North	1993	1993-94	Target: 90 cm mineral 10 cm peat	1993 6349 wS planted (target of 3489 trees ha^{-1}) followed by 2000 trees ha^{-1} over 2.8 ha in 1994		
S2 South	1991	1992	90 cm DP	2000 stems ha^{-1}		
SW30	1999		20 cm of peat over 80 cm of secondary	2000 stems ha^{-1}		5:1 slope (50mX100m)
S1 upper	1987	1990 & 2002	70 cm muskeg and secondary	22000 jP replant 2000 tA ha^{-1}	Super 45s Spencer-Lemaire 750ml containers	Planted by professional planters – Evergreen (Grand Prairie)
S1 lower	Pre-1980	1980	Not capped or only a skiff (lots of experimentation with fertilizer & seed) 7.5 cm muskeg applied to an area	target of 5000 stems ha^{-1} trees and shrubs	Spencer-Lemaire (Hillson, Tinus, Five), styroblocks (4A, 7, 8, 20), few paperpot	
S4 (Gateway Hill)	1990	1990	184 cm from S4 stockpile (mixture of peat and mineral, sometimes not very nice mineral – originally waste)	2261 stems ha^{-1}		6:1 slopes flattened from planned 4:1
S27 (Bison Hill)	1993-94	1994	1 m DP mineral soil; part of the area with 90 cm mineral soil and 10 cm peat	Target 2000 stems ha^{-1}		

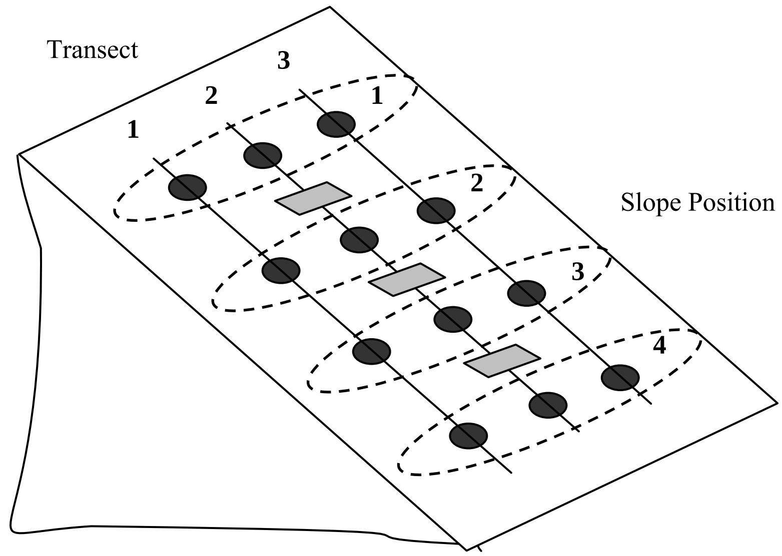


Figure B.2. Basic sampling design used for three reconstructed mixedwood overburden sites (SW30, S2-south, and S4) in Chapter 3 to collect root core and soil samples (dark gray circles). Three equidistant transects (black lines) run parallel to the slope direction with four relatively equidistant sampling points along each transect (4 slope positions). Bulk density pits (light gray parallelograms) were dug at three slope positions on the central transect (except at S4) between the four other sampling points.

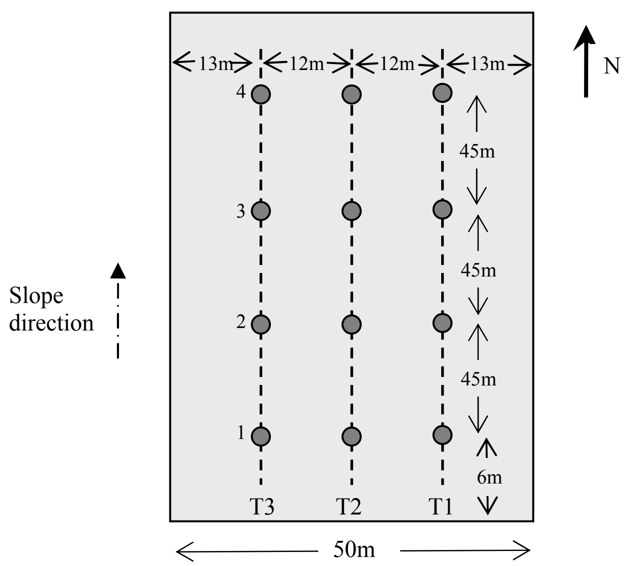


Figure B.3. Sampling design for SW30 showing slope and aspect direction and distances between transects (T1, T2, T3) and sampling points.

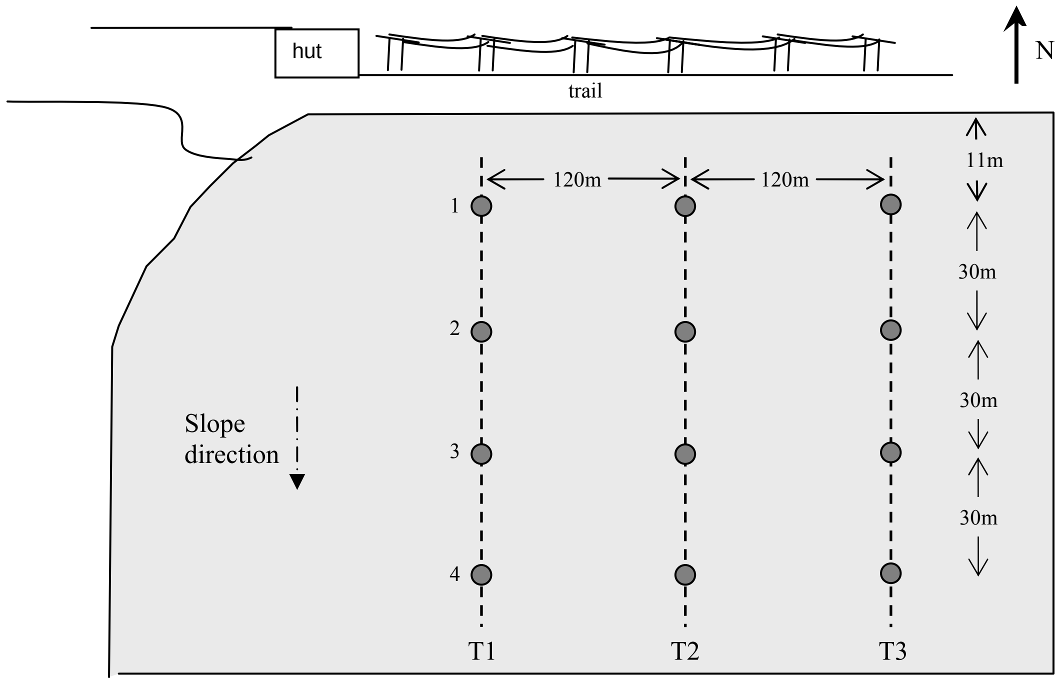


Figure B.4. Sampling design for S2 showing slope and aspect direction and distances between transects (T1, T2, T3) and sampling points.

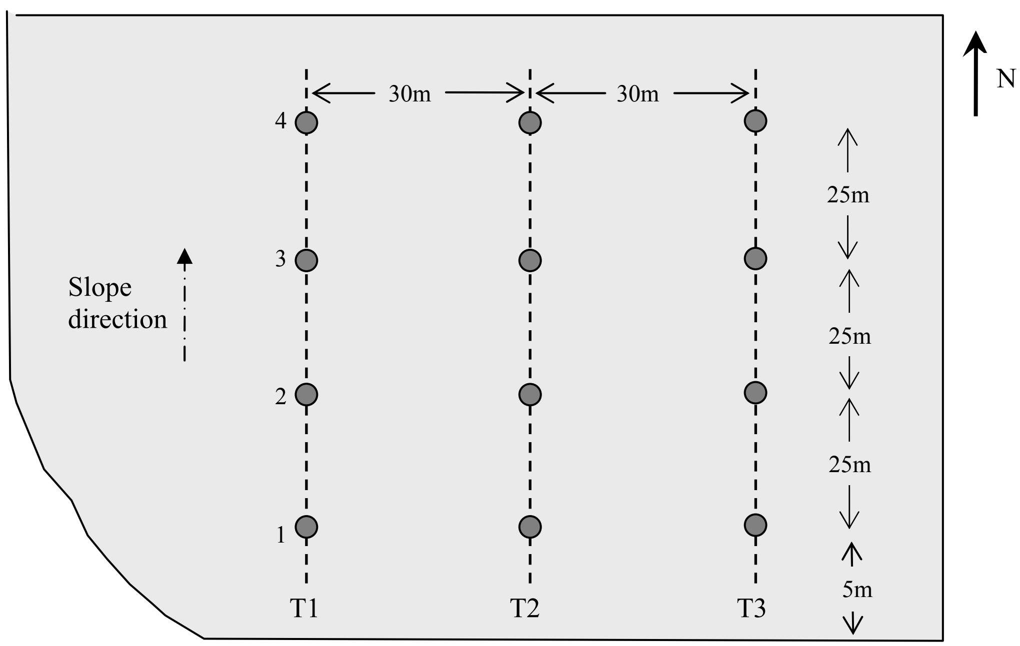


Figure B.5. Sampling design for S4 showing slope and aspect direction and distances between transects (T1, T2, T3) and sampling points.

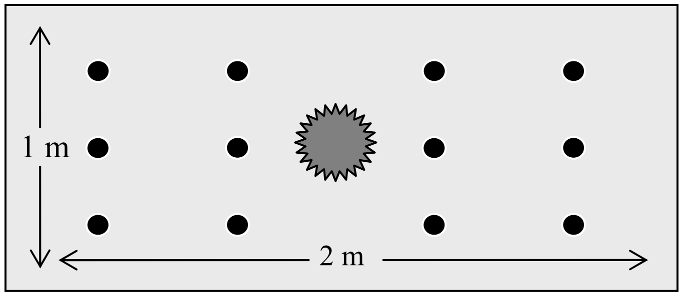


Figure B.6. Individual plot layout for the Sr tracer study (Chapter 4). The central star represents a tree and each smaller circle represents one augered hole for $SrCl_2$ addition at depth.

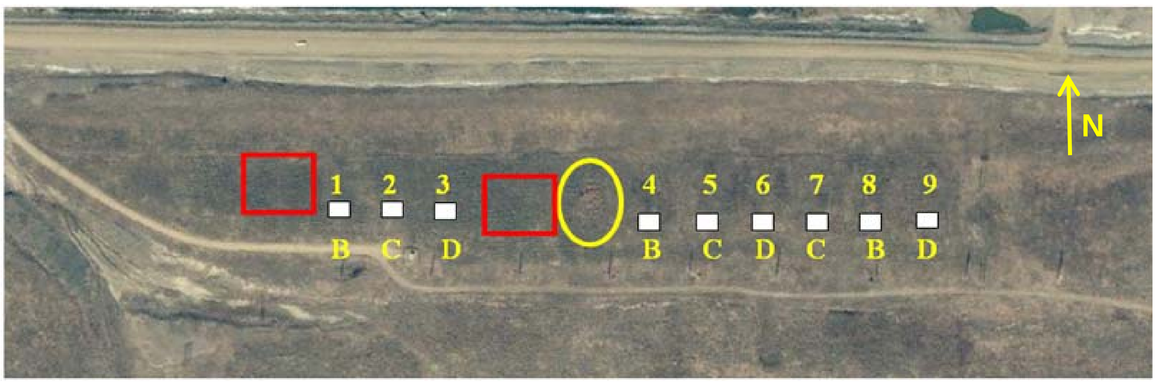


Figure B.7. Plot layout (small white rectangles) at S2 indicating tree number and treatment (C, control; B, broadcast; and D, depth). The red squares represent regional test plots; the yellow oval is an area planted to Siberian larch.

Figure B.8. Plot layout (white rectangles) at MLSB Cell 19 (wS) indicating tree number and treatment (C, control; B, broadcast; and D, depth). The red square represents a regional test plot.

Figure B.9. Plot layout (white rectangles) at S27 indicating tree number and treatment (C, control; B, broadcast; and D, depth). The green and white striped bar represents a bison pasture gate.

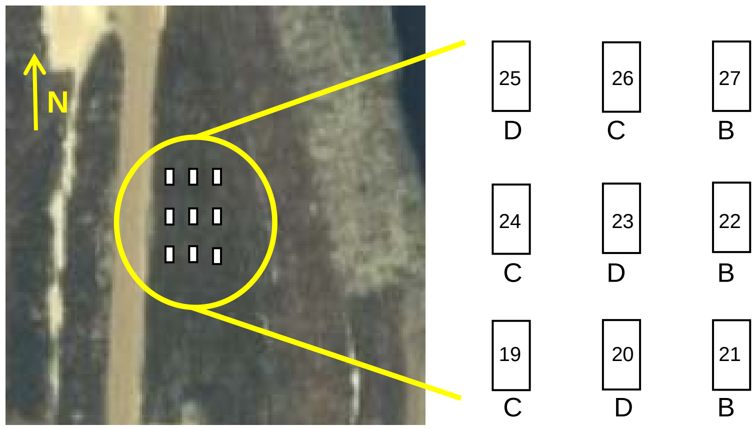


Figure B.10. Plot layout (white rectangles) at MLSB Cell 6 indicating tree number and treatment (C, control; B, broadcast; and D, depth).

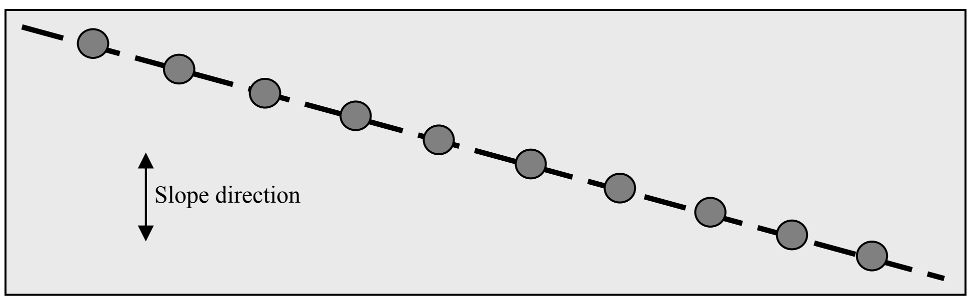


Figure B.11. Schematic diagram showing trees selected for excavation (gray circles) along a diagonal transect across slope (Chapter 5).

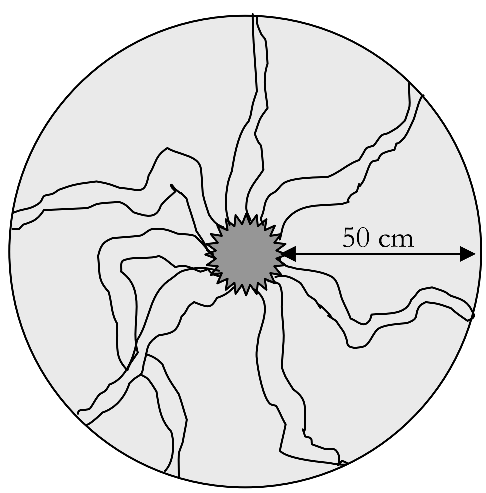


Figure B.12. Schematic diagram of tree root excavation to a 50 cm radius from the stem base.

Table B.2. GPS locations for root core and soil sample points at SW30, S2, and S4 (Chapter 3) collected using a handheld GPS unit.

	GPS Coordinates†	
Sample Location ID‡	**Northing**	**Easting**
	SW30	
SW3011	0462425	6317055
SW3012	0462385	6317123
SW3013	0462368	6317130
SW3014	0462340	6317173
SW3021	0462411	6317046
SW3022	0462377	6317094
SW3023	0462359	6317119
SW3024	0462334	6317153
SW3031	0462403	6317032
SW3032	0462374	6317075
SW3033	0462349	6317113
SW3034	0462319	6317150
	S2	
S211	0464064	6317126
S212	0464077	6317098
S213	0464087	6317072
S214	0464093	6317042
S221	0464177	6317169
S222	0464185	6317136
S223	0464199	6317108
S224	0464214	6317082
S231	0464295	6317197
S232	0464307	6317162
S233	0464312	6317133
S234	0464319	6317105
	S4	
S411	0465437	6317315
S412	0465436	6317332
S413	0465434	6317364
S414	0465437	6317384
S421	0465465	6317319
S422	0465457	6317340
S423	0465466	6317352
S424	0465486	6317387
S431	0465495	6317320
S432	0465488	6317345
S433	0465492	6317358
S434	0465508	6317384

† Handheld GPS unit accuracy was limited to 24 m at times.
‡ Identification consists of the site name, transect number, and slope position number in sequence. For example, S423 refers to site S4, transect 2, slope position 4.

Table B.3. GPS locations of $SrCl_2$ treatment plots at S2, S27, MLSB Cell 6, and Cell 19 (Chapter 4) collected using a handheld GPS unit.

		GPS Coordinates†	
Tree	**Treatment‡**	**Northing**	**Easting**
		S2	
1	B	0463933	6317169
2	C	0463962	6317177
3	D	0464000	6317188
4	B	0464134	6317212
5	C	0464159	6317218
6	D	0464194	6317226
7	C	0464227	6317237
8	B	0464257	6317247
9	D	0464289	6317260
		MLSB Cell 19	
10	B	0460737	6328732
11	C	0460760	6328710
12	D	0460784	6328688
13	D	0460815	6328667
14	B	0460836	6328643
15	C	0460859	6328623
16	B	0460881	6328600
17	C	0460905	6328579
18	D	0460938	6328553
		MLSB Cell 6	
19	C	0459736	6324986
20	D	0459771	6324971
21	B	0459775	6324980
22	B	0459774	6325023
23	D	0459752	6325021
24	C	0459731	6325020
25	D	0459729	6325040
26	C	0459762	6325045
27	B	0459782	6325046
		S27	
28	D	0463284	6317580
29	B	0463301	6317580
30	C	0463319	6317582
31	D	0463338	6317584
32	C	0463357	6317588
33	B	0463377	6317595
34	B	0463392	6317594
35	C	0463411	6317597
36	D	0463429	6317600

† Handheld GPS unit accuracy was limited to 24 m at times.

‡ B – broadcast, C – control, D – depth placement of $SrCl_2$

Table B.4. GPS locations of excavated trees at S1-10, S1-20, MLSB Cell 6, and Cell 18 (Chapter 5) collected using a handheld GPS unit.

		GPS Coordinates†	
Sample Location ID‡	**Tree**	**Northing**	**Easting**
	S1-10yr		
S11001	1	0462530	6316628
S11002	2	0462505	6316617
S11003	3	0462479	6316609
S11004	4	0462451	6316597
S11005	5	0462424	6316586
S11006	6	0462399	6316575
S11007	7	0462374	6316568
S11008	8	0462352	6316560
S11009	9	0462334	6316550
S11010	10	0462328	6316555
	S1-20yr		
S12001	1	0462122	6316493
S12002	2	0462165	6316499
S12003	3	0462209	6316505
S12004	4	0462256	6316512
S12005	5	0462304	6316494
S12006	6	0462345	6316507
S12007	7	0462389	6316520
S12008	8	0462433	6316511
S12009	9	0462480	6316506
S12010	10	0462525	6316521
	MLSB Cell 6		
C601	1	0459734	6325127
C602	2	0459736	6325107
C603	3	0459739	6325080
C604	4	0459739	6325057
C605	5	0459743	6325032
C606	6	0459749	6325009
C607	7	0459749	6324984
C608	8	0459746	6324957
C609	9	0459743	6324919
C610	10	0459770	6324900
	MLSB Cell 18		
C1801	1	0460761	6328939
C1802	2	0460755	6328966
C1803	3	0460735	6328968
C1804	4	0460733	6328987
C1805	5	0460716	6329007
C1806	6	0460693	6329010
C1807	7	0460678	6329024
C1808	8	0460772	6328929
C1809	9	0460781	6328934
C1810	10	0460796	6328921

† Handheld GPS unit accuracy was limited to 24 m at times.

‡ Identification consists of the site name and tree number in sequence. For example, S12009 refers to site S1-20 and tree number 4.

APPENDIX C: REGRESSION CALCULATIONS

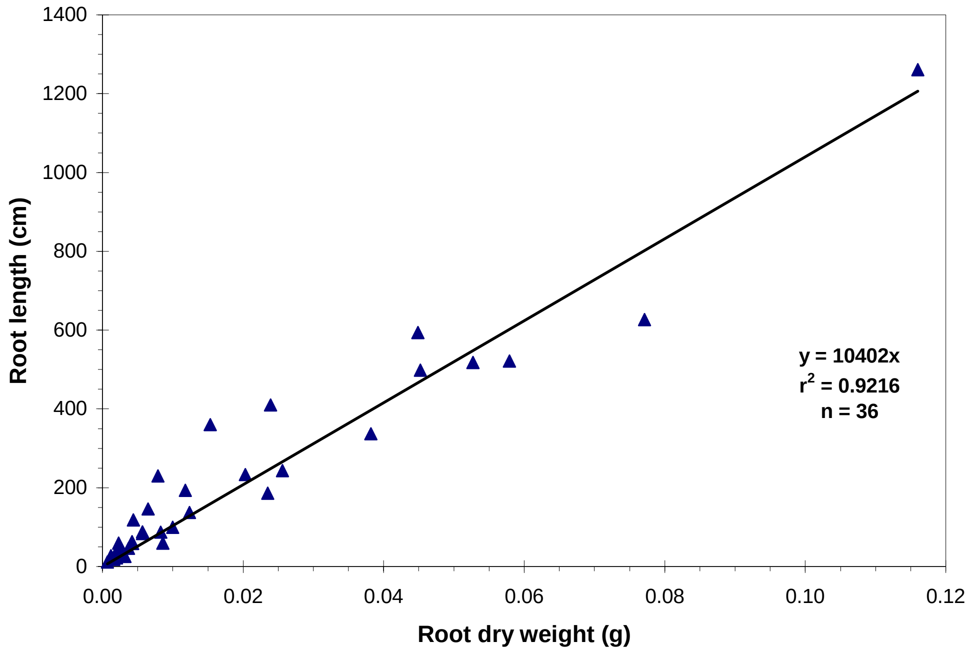


Figure C.1. Regression equation used to calculate root length from root dry weight measurements for samples from SW30.

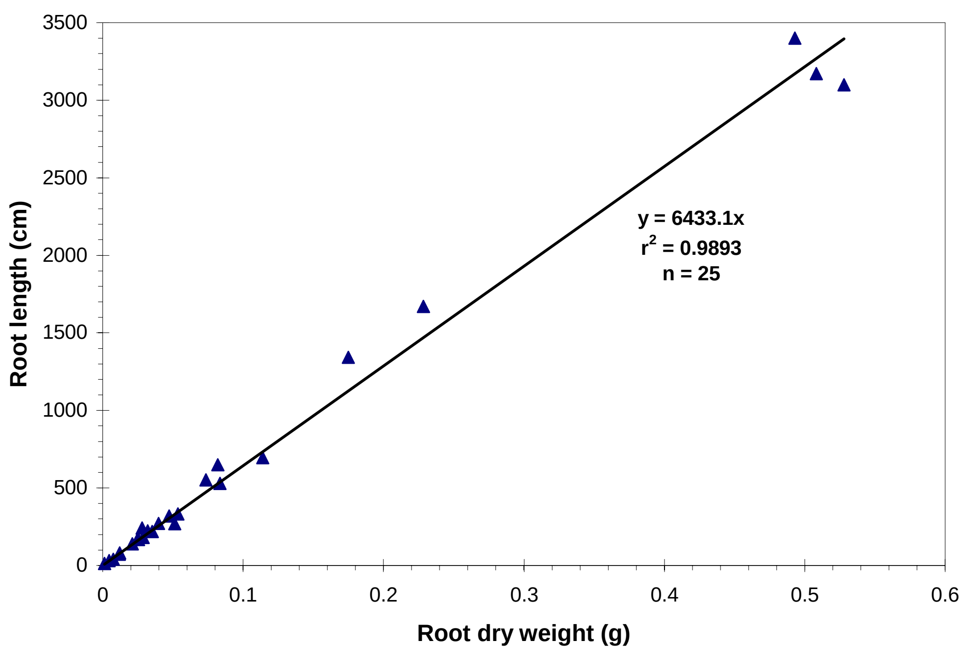


Figure C.2. Regression equation used to calculate root length from root dry weight measurements for samples from S2.

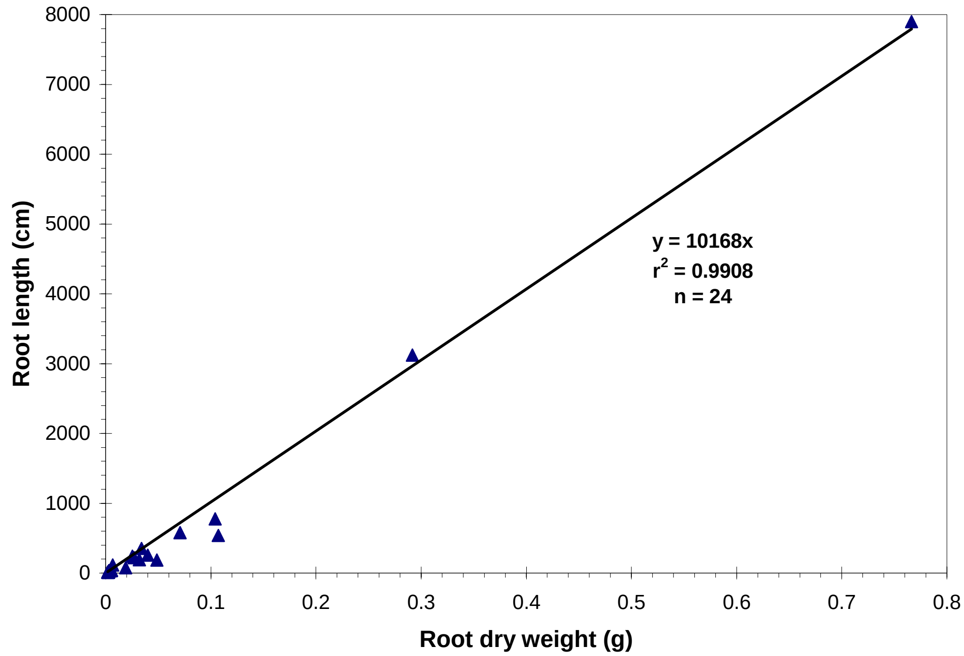


Figure C.3. Regression equation used to calculate root length from root dry weight measurements for samples from S4.

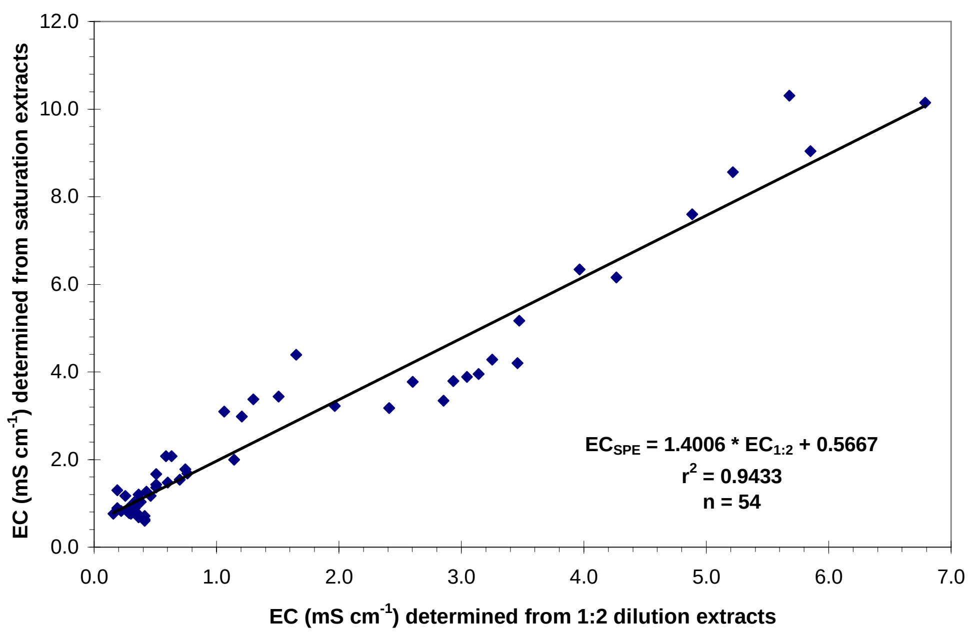


Figure C.4. Regression equation used to calculate saturated paste extract (SPE) values from 1:2 dilution extract values for electrical conductivity (EC).

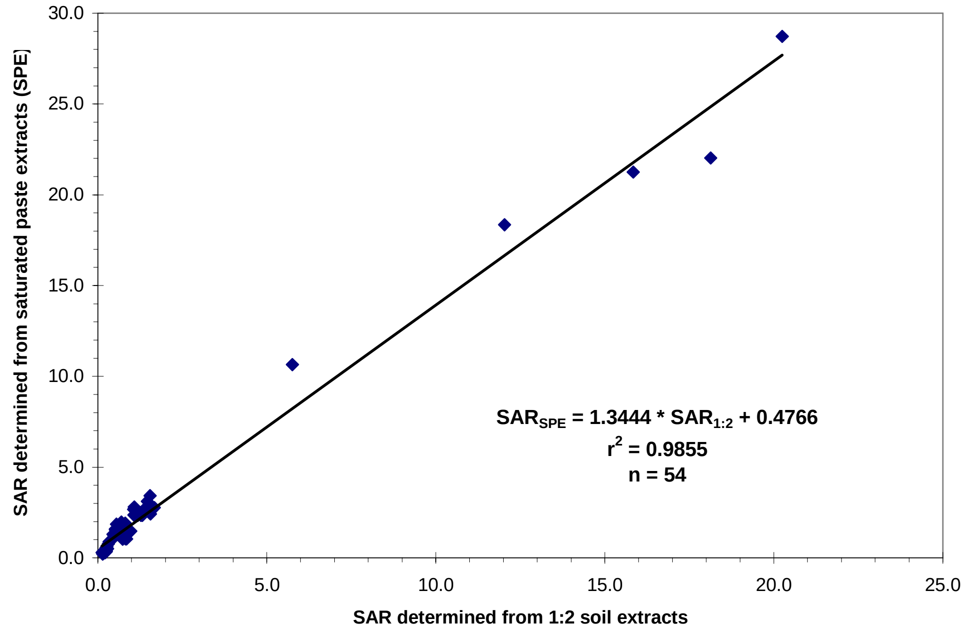


Figure C.5. Regression equation used to calculate saturated paste extract (SPE) values from 1:2 dilution extract values for sodium absorption ratio (SAR).

APPENDIX D: ROOT AND SOIL DATA FROM SW30, S2, AND S4 GRAPHED USING THE SOIL/OVERBURDEN INTERFACE AS THE REFERENCE POINT

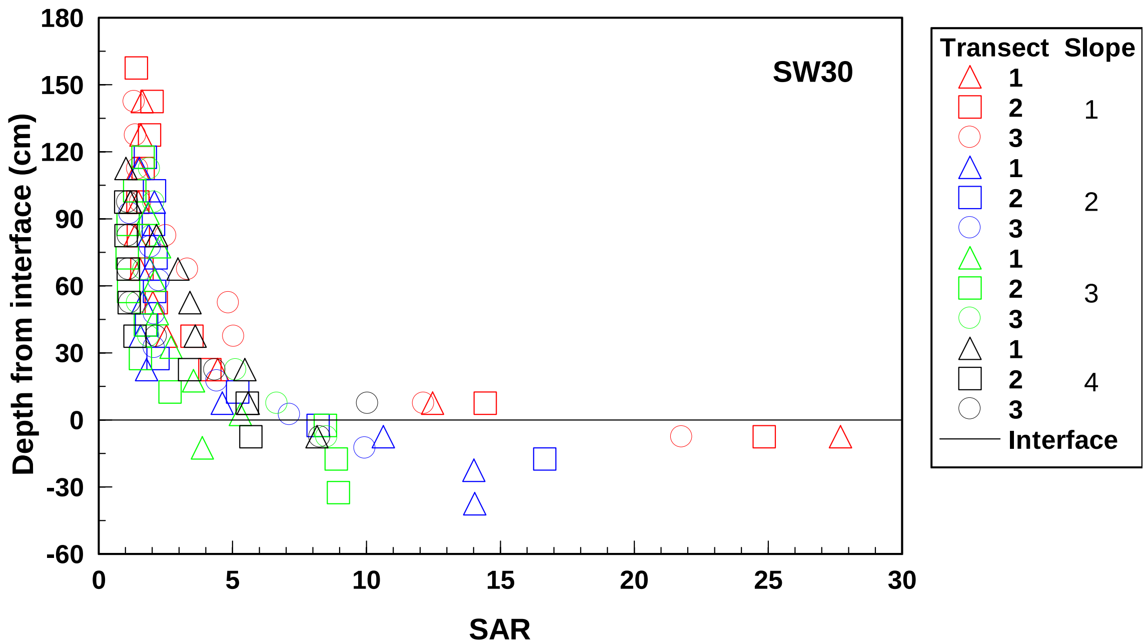


Figure D.1. Sodium absorption ratio (SAR) calculated for saturated paste extracts of soil samples collected at SW30.

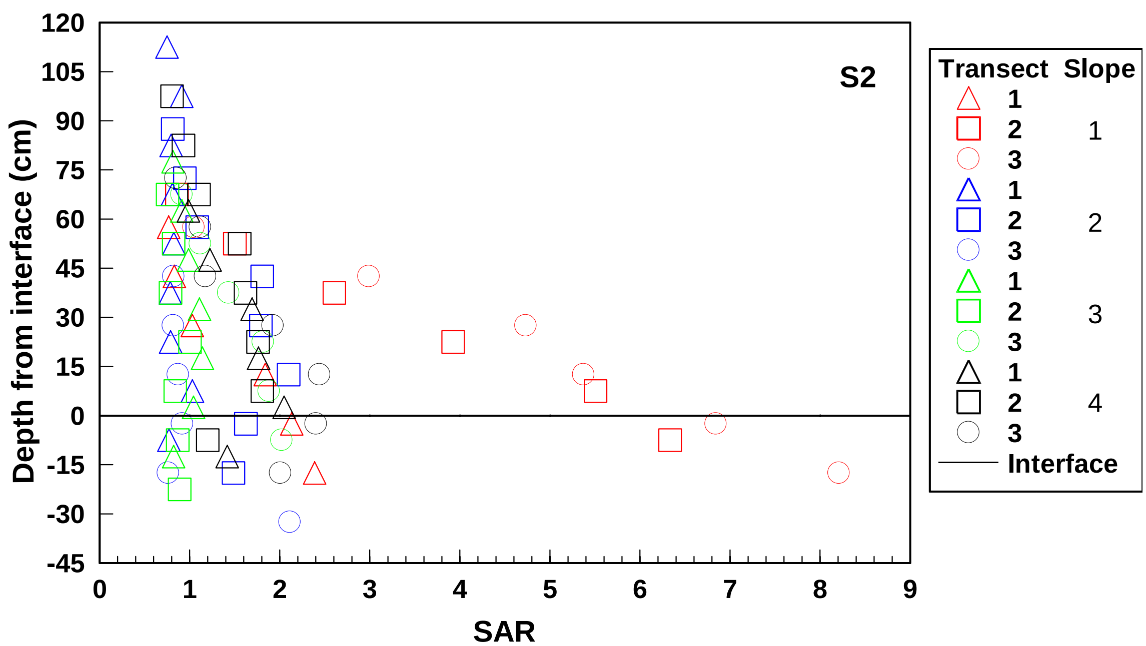


Figure D.2. Sodium absorption ratio (SAR) calculated for saturated paste extracts of soil samples collected at S2.

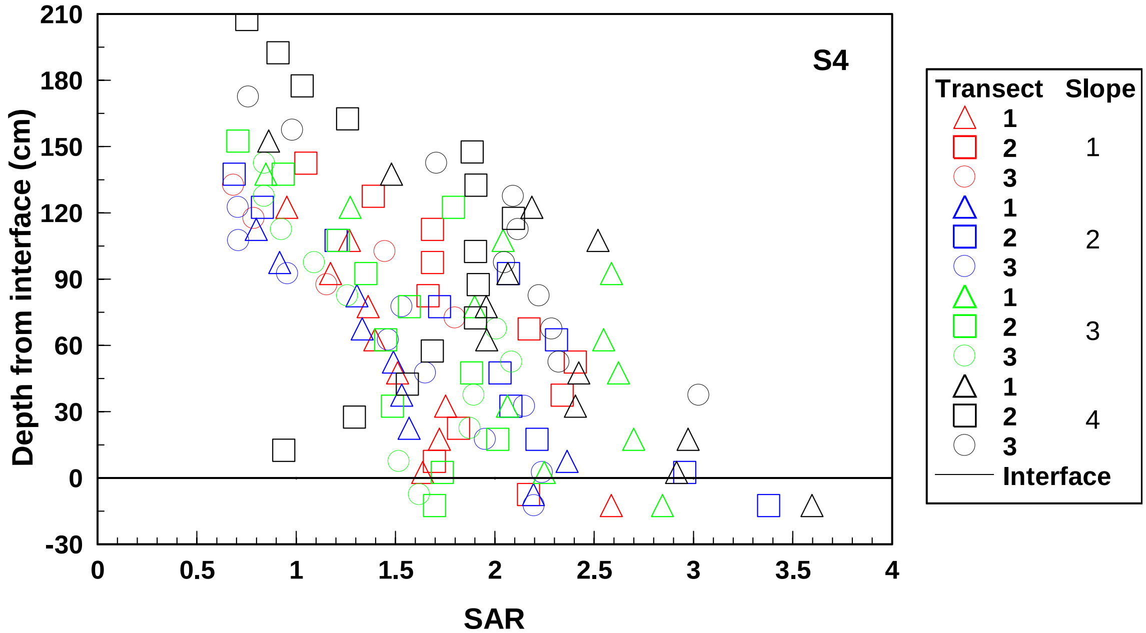


Figure D.3. Sodium absorption ratio (SAR) calculated for saturated paste extracts of soil samples collected at S4.

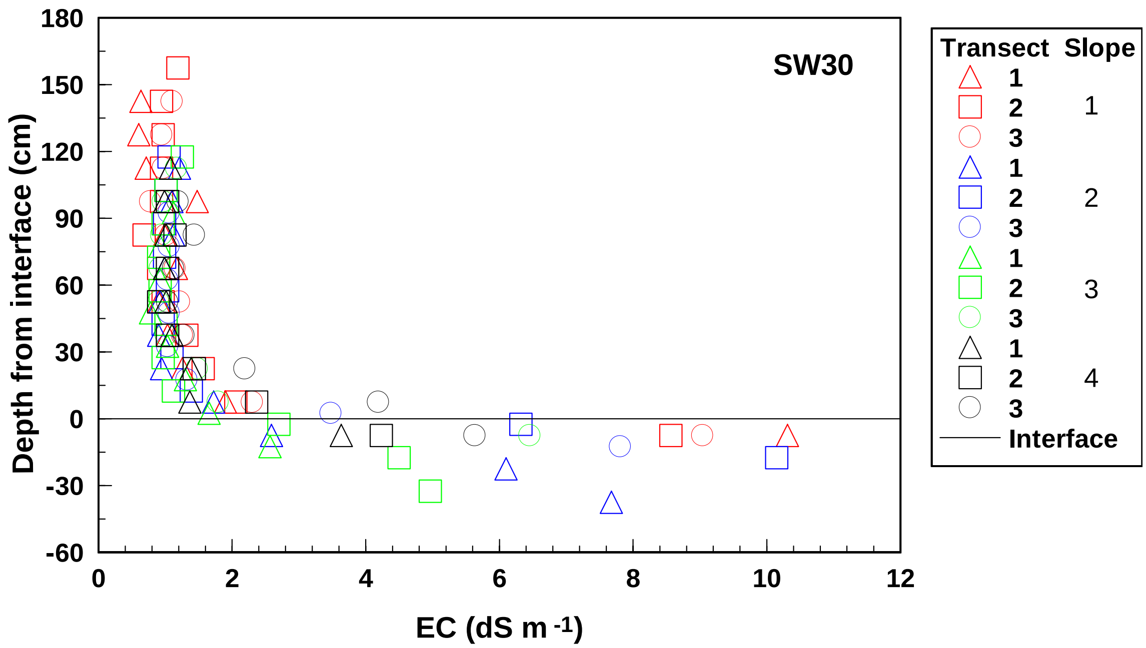


Figure D.4. Electrical conductivity (EC) calculated for saturated paste extracts of soil samples collected at SW30.

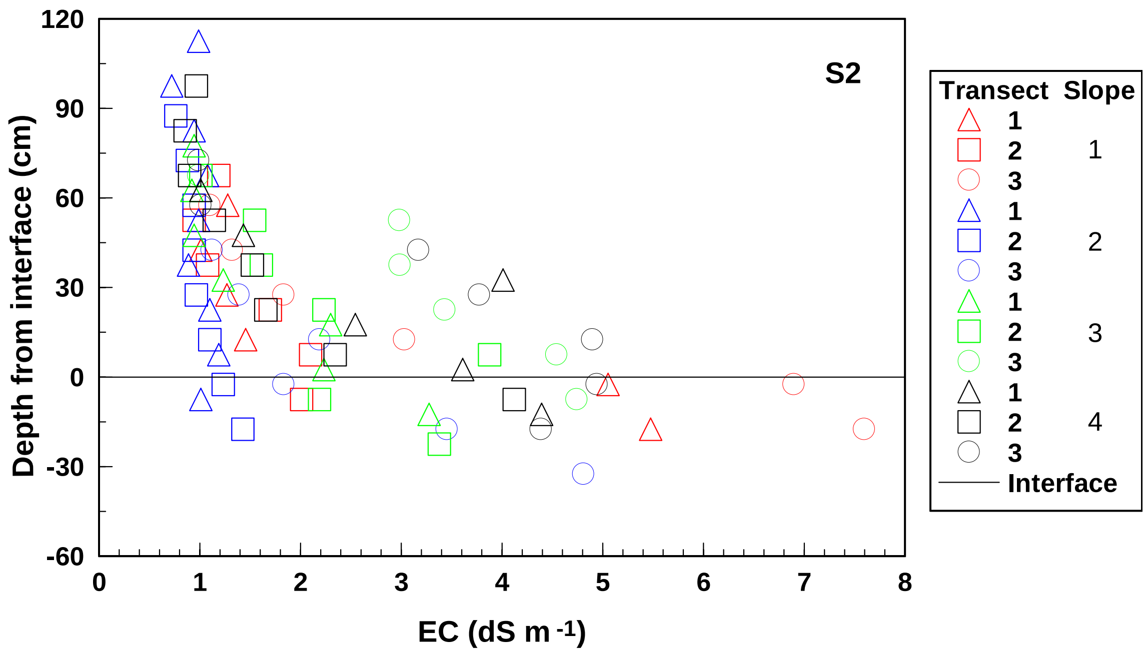


Figure D.5. Electrical conductivity (EC) calculated for saturated paste extracts of soil samples collected at S2.

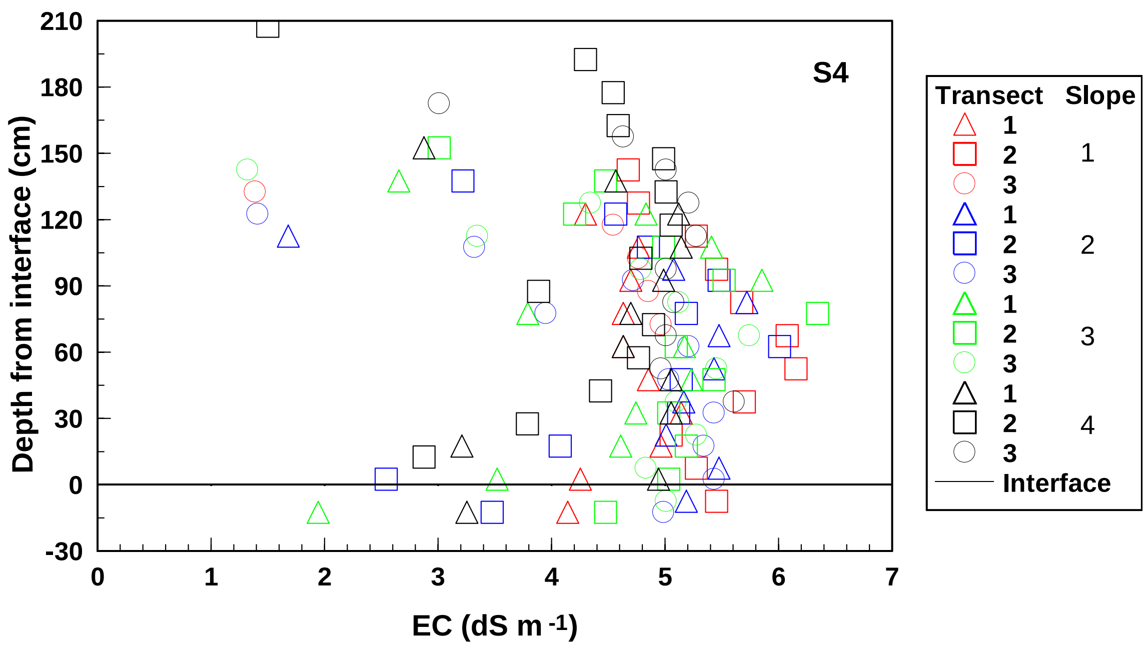


Figure D.6. Electrical conductivity (EC) calculated for saturated paste extracts of soil samples collected at S4.

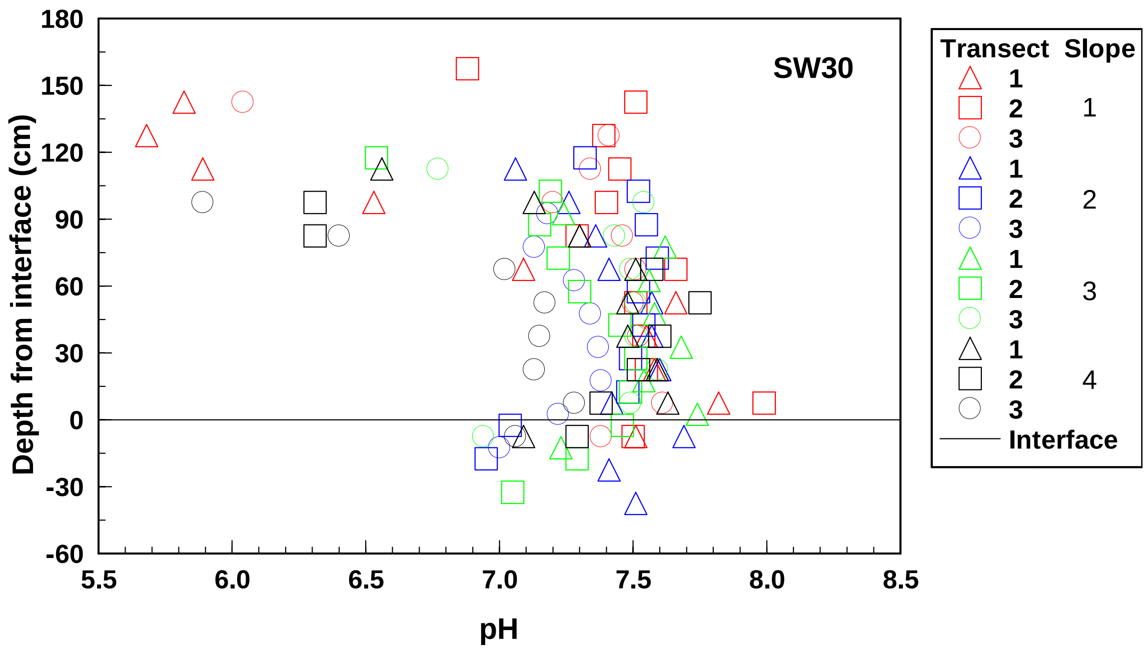


Figure D.7. Measured pH values for saturated pastes of soil samples collected at SW30.

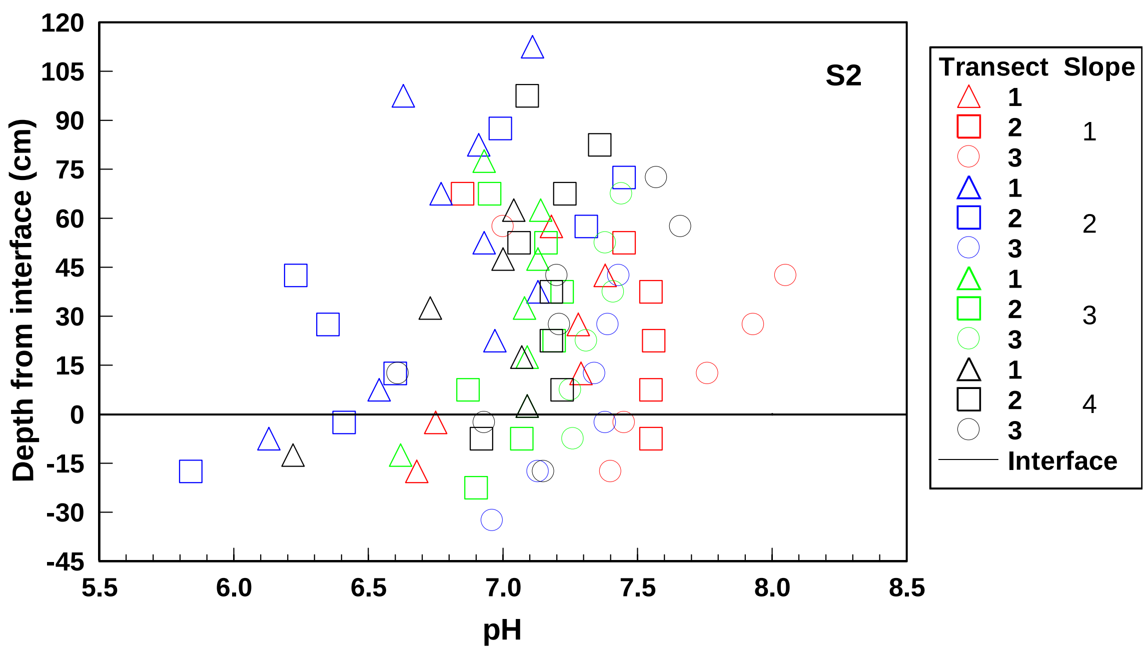


Figure D.8. Measured pH values for saturated pastes of soil samples collected at S2.

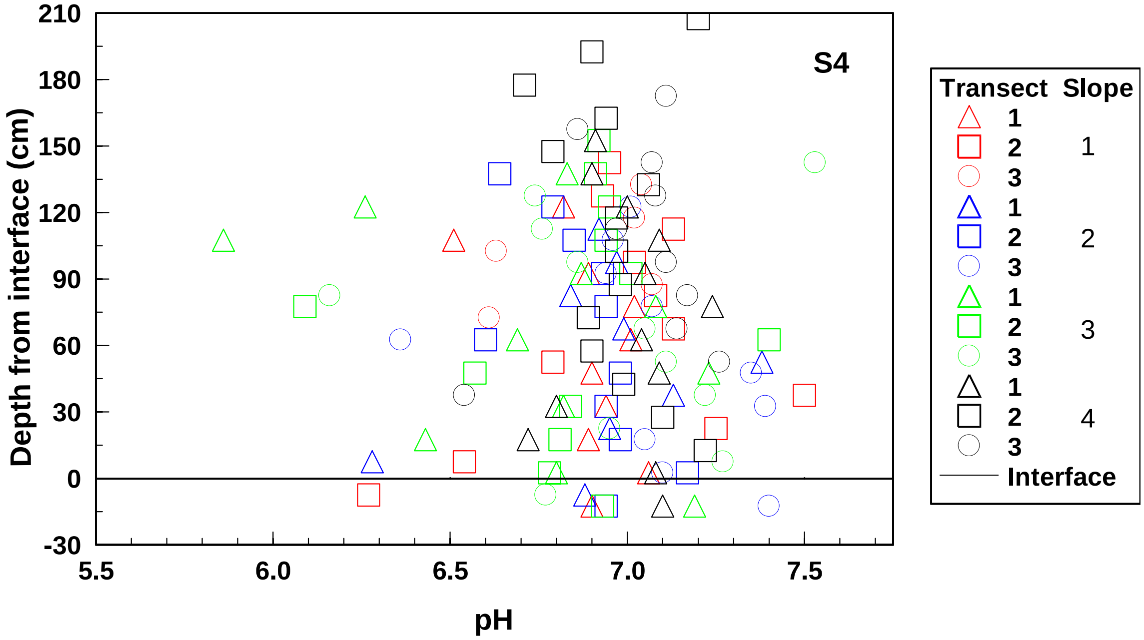


Figure D.9. Measured pH values for saturated pastes of soil samples collected at S4.

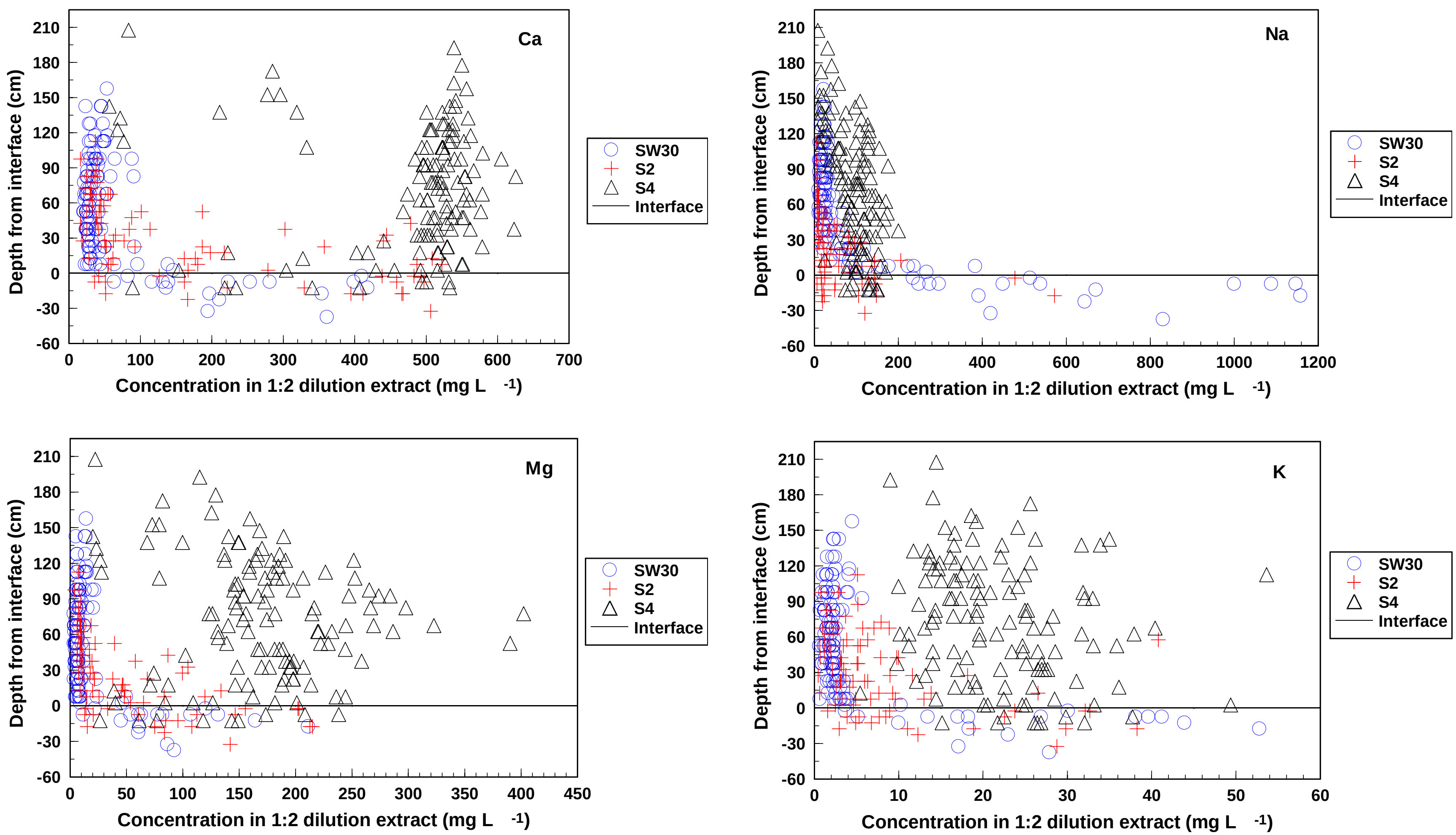


Figure D.10. Soluble cation concentrations (Ca, Mg, Na, and K) in 1:2 dilution extracts for sites SW30, S2, and S4.

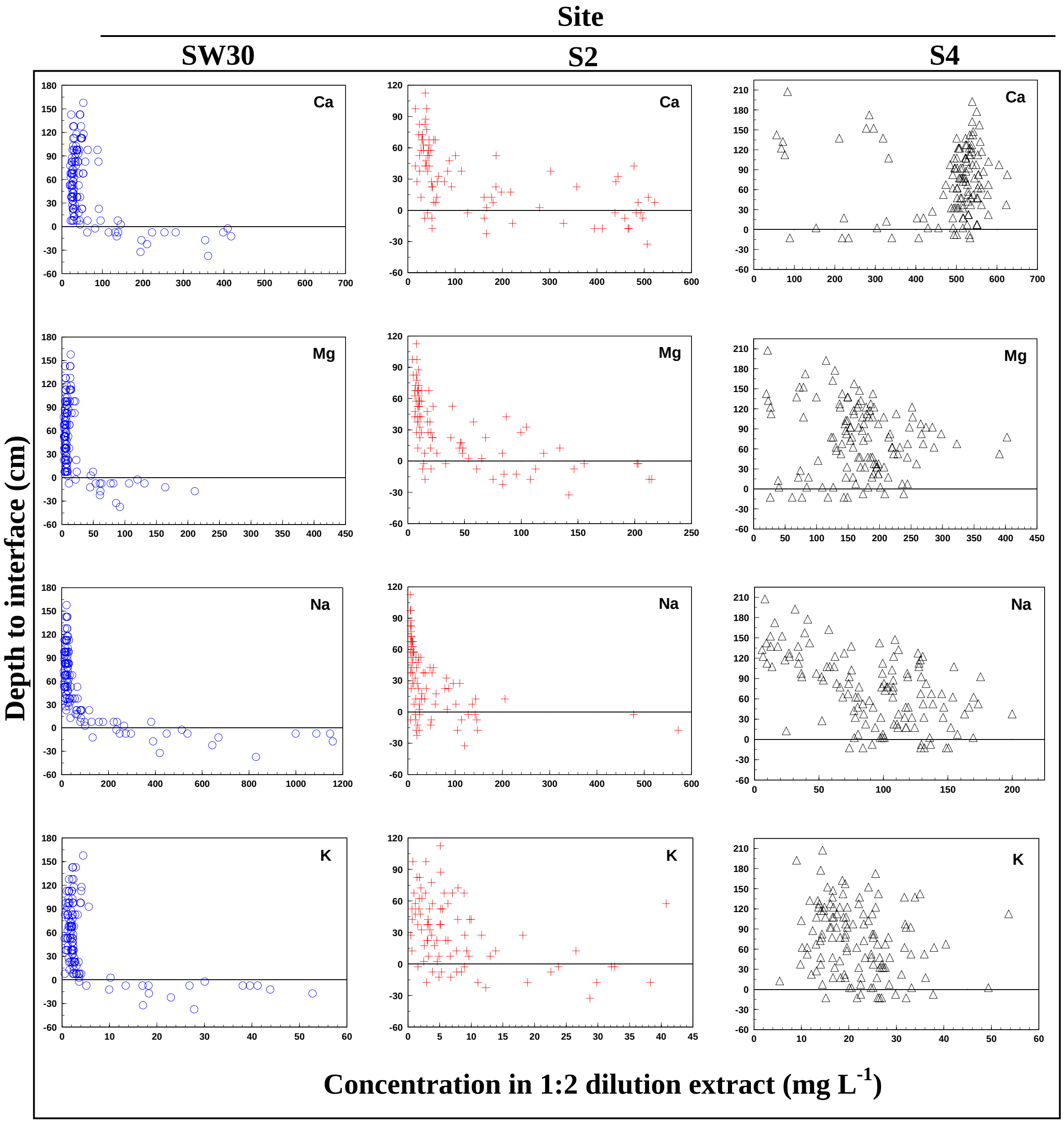


Figure D.11. Individual soluble cation concentrations (Ca, Mg, Na, and K) in 1:2 dilution extracts for each site (SW30, S2, and S4).

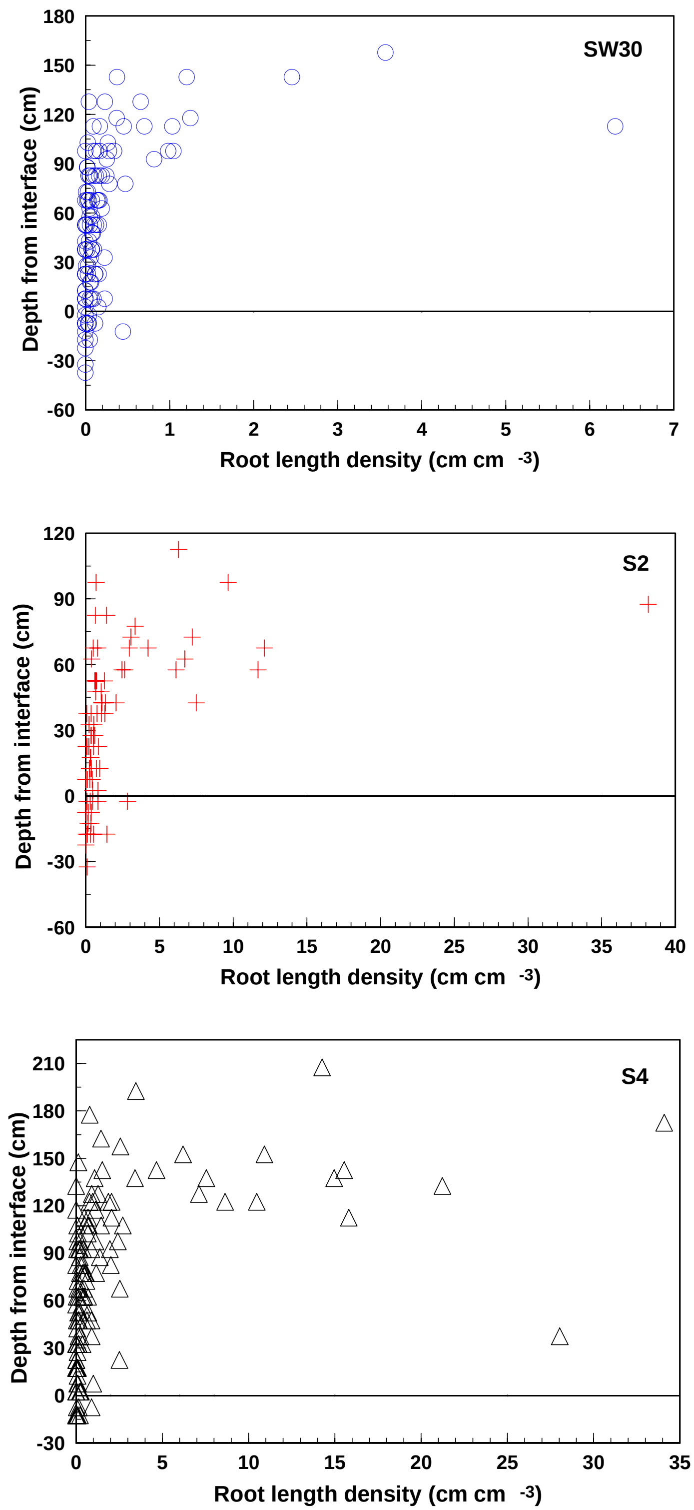


Figure D.12. Root length density distributions for each site (SW30, S2, and S4).

APPENDIX E: UNDERSTORY ASSESSED FOR PERCENTAGE COVER

Table E.1. Percentage cover by understory vegetation at each sampling location for all reclaimed mixedwood sites.

Location†				Understory species‡											
Transect	**Slope**	**Bare§**	**Veg**	**cl**	**gr**	**da**	**sth**	**bft**	**fw**	**ht**	**rb**	**cth**	**pv**	**mv**	**sb**
							SW30								
1	1	21	79	30	30		2			7		10			
1	2	14	86	40	40		1		5						
1	3	5	95	75	10		5			5					
1	4	2	98	70	5				15				8		
2	1	8	92	15	60	15	1		<1	1					
2	2	6	94	30	50		12			1			1		
2	3	3	97	60	35	1	<1		1						
2	4	5	95	70	10	5			10						
3	1	10	90	40	40		1		1	5	1	2			
3	2	7	93	80	10		2		1						
3	3	0	100	70	20				10						
3	4	0	100	82	7	2	5		4						
							S2								
1	1	5	95	85	10										
1	2	33	67	60		5			2						
1	3	0	100	90	10										
1	4	8	92	20		10		60	2						
2	1	9	91	40	5	6		40							
2	2	10	90	40	40	5			5						
2	3	27	73	50	6	15			1	1					
2	4	28	72	60	5	5			2						
3	1	8	92	70	5	15			2						
3	2	0	100	70	10	15					5				
3	3	5	95	45	1	1	3							45	
3	4	20	80	80											
							S4								
1	1	20	80	55	5	20									
1	2	0	100		50	40	9			1					
1	3	3	97	5	35	35	20			2					
1	4	28	72	40		20	10			1					1
2	1	5	95	50	4	15	25			1					
2	2	3	97	1		75	20			1					
2	3	0	100	40		40	10			10					
2	4	19	81	25	5	25	25			1					
3	1	5	95	15	25	50				5					
3	2	13	87	10	25	30	20			2					
3	3	0	100	25	20	50	5								
3	4	5	95	35		55	5								

† Location refers to the transect and slope positions as outlined in Appendix B.

‡ cl, clover; gr, grasses; da, dandelion; sth, sow thistle; bft, bird's-foot trefoil; fw, fireweed; ht, horsetail; rb, raspberry; cth, Canada thistle; pv, pea vine; mv, milk vetch; sb, strawberry.

§ Bare, amount of bare ground visible; Veg, the amount of ground covered by all vegetation.

APPENDIX F: BACKGROUND FOLIAR SR AND SOLUBLE SOIL CA

Table F.1. Mean (±1 SD) background foliar Sr concentrations for understory vegetation at each reclaimed site.

	Site				
Spp.†	**S27**	**Cell 19**	**Cell 6**	**S2**	**All sites**
	------------------------- $\mu g\ g^{-1}$ -------------------------				
bb			105.53‡		105.53
bft		59.51 ± 0.63			59.51 ± 0.63
bP		27.05 ± 6.40	74.95 ± 1.55	29.69 ± 6.54	34.19 ± 16.98
cl	71.12	141.98	81.04 ± 14.33	77.39 ± 9.16	83.47 ± 21.01
da		51.37		25.03 ± 5.06	31.61 ± 13.80
dw		56.22		32.58	44.40 ± 16.72
fw	35.04 ± 1.21		62.67		44.25 ± 15.98
gb			81.17 ± 1.81		81.17 ± 1.81
gr	23.58 ± 9.86	31.84 ± 12.62	26.97 ± 8.13	22.59 ± 7.77	25.25 ± 9.30
kk			28.28 ± 5.44		28.28 ± 5.44
pv			103.47		103.47
rb		26.65 ± 2.96			26.65 ± 2.96
sb	28.06		92.32 ± 16.70		85.18 ± 26.51
sth	44.42 ± 6.40	37.23 ± 7.39	59.01 ± 3.10	16.57 ± 0.68	40.15 ± 12.35
tA				30.01	30.01
wi	43.33			30.33 ± 0.45	34.66 ± 7.51

† bb – buffalo berry (*Shepherdia* Nutt.); bft – bird's foot trefoil (*Lotus corniculatus* L.); bP – balsam poplar (*Populus balsamifera* L.); cl – clover (*Melilotus officinalis* (L.) Lam. and *M. alba* Medikus); da – dandelion (*Taraxacum offininale* G.H. Weber ex Wiggers); dw – dogwood (*Cornus sericea* L.); fw – fireweed (*Chamerion angustifolium* (L.) Holub); gb – goose berry (*Ribes* L.); gr – grasses (various); kk – kinnikinnick (*Arctostaphylos uva-ursi* (L.) Spreng.); pv – pea vine (*Lathyrus* L.); rb – raspberry (*Rubus* L.); sb – strawberry (*Fragaria* L.); sth – sow thistle (*Sonchas oleraceus* L.); tA – trembling aspen (*Populus tremuloides* Michx.); wi – Willow (*Salix* L.). (Integrated Taxonomic Information System, 2008).

‡ For samples where no SD is given, there was only 1 sample collected.

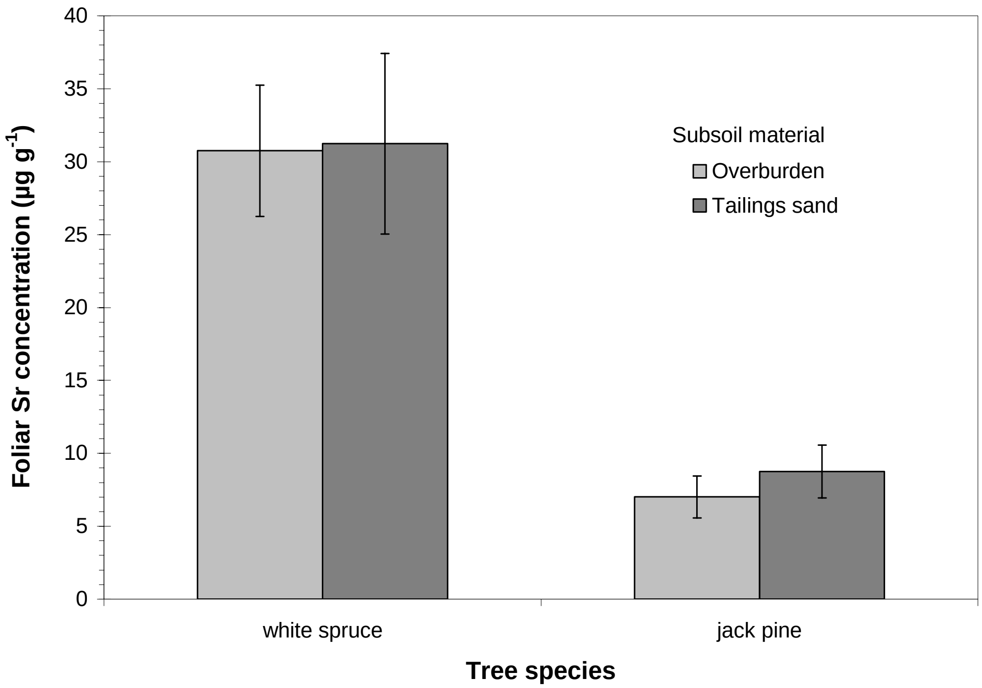


Figure F.1. Mean background Sr concentrations in white spruce (S2 and Cell 19) and jack pine (S27 and Cell 6) needles at each site. Error bars indicate ± 1SD.

Table F.2: Mean (± 1 SD) soluble Ca in soil of plots treated at soil surface or depth as determined by 1:2 dilution extracts.

	Treatment	
Site	**Broadcast**	**Depth†**
	----------------------- mg L^{-1} ----------------------	
S2	50.85 ± 4.11	214.40 ± 241.77
S27	72.27 ± 36.14	126.79 ± 133.27
Cell 6	43.60 ± 5.60	24.54 ± 10.55
Cell 19	67.35 ± 15.45	83.12 ± 70.25

† Depth treatments were applied at 85 cm for Cell 6, and to 100 cm for S2, S27, , and Cell 19.

APPENDIX G: ANOVA TABLES COMPARING SR CONCENTRATION IN TREE NEEDLES

Table G.1. ANOVA tables for fall foliar Sr concentrations at S27, MLSB Cell 6, S2, and MLSB Cell 19.

Source of Variation	df†	Mean Square	F‡	*p*
		S27		
Corrected model	2	.137	.545	.606
Intercept	1	2.333	9.318	.022
Treatment	2	.137	.545	.606
Error	6	.250		
		MLSB Cell 6		
Corrected model	2	9.617	4.607	.061
Intercept	1	66.681	31.944	.001
Treatment	2	9.617	4.607	.061
Error	6	2.087		
		S2		
Corrected model	2	10.484	.395	.690
Intercept	1	5770.548	217.416	.000
Treatment	2	10.484	.395	.690
Error	6	26.541		
		MLSB Cell 19		
Corrected model	2	128.160	2.416	.170
Intercept	1	6708.983	126.454	.000
Treatment	2	128.160	2.416	.170
Error	6	53.055		

† Degrees of freedom
‡ F ratio
§ R squared (S27 = .154; MLSB Cell 6 = .606; S2 = .116; MLSB Cell 19 = .261)

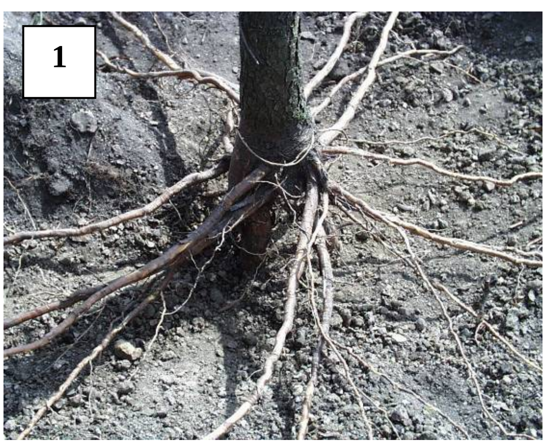
Table G.2. ANOVA tables for 2004 foliar Sr concentrations at S27, MLSB Cell 6, S2, and MLSB Cell 19.

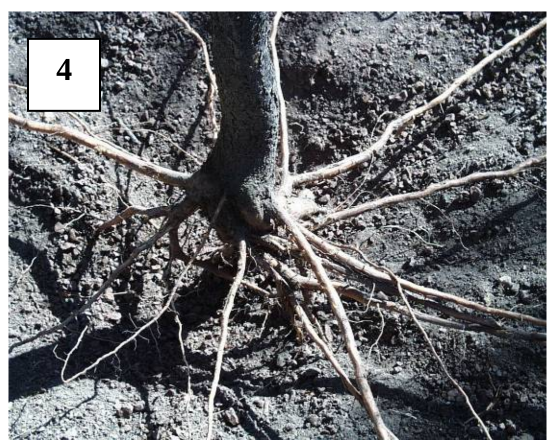
Source of Variation	**df†**	**Mean Square**	**F‡**	***p***
		S27		
Corrected model	2	.340	.270	.772
Intercept	1	43.546	34.530	.001
Treatment	2	.340	.270	.772
Error	6	1.261		
		MLSB Cell 6		
Corrected model	2	29.216	.705	.531
Intercept	1	17078.950	411.999	.000
Treatment	2	29.216	.705	.531
Error	6	41.454		
		S2		
Corrected model	2	1.769	1.262	.349
Intercept	1	101.120	72.171	.000
Treatment	2	1.769	1.262	.349
Error	6	1.401		
		MLSB Cell 19		
Corrected model	2	178.077	1.817	.242
Intercept	1	19152.331	195.370	.000
Treatment	2	178.077	1.817	.242
Error	6	98.031		

† Degrees of freedom
‡ F ratio
§ R squared (S27 = .082; MLSB Cell 6 = .296.; S2 = .190; MLSB Cell 19 = .377)

APPENDIX H: EXAMPLES OF KINKING AND COILING OF ROOT SYSTEMS AND THE RATING GIVEN TO THEM

Kinking



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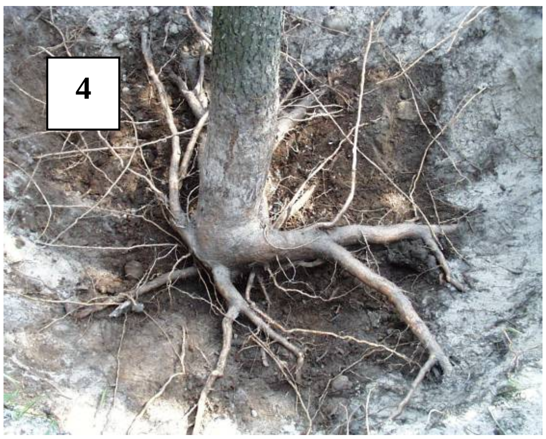
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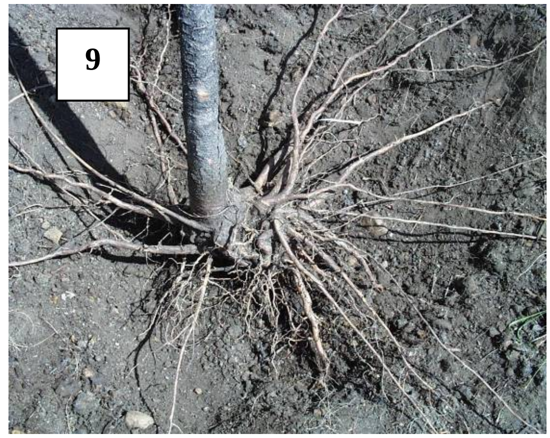
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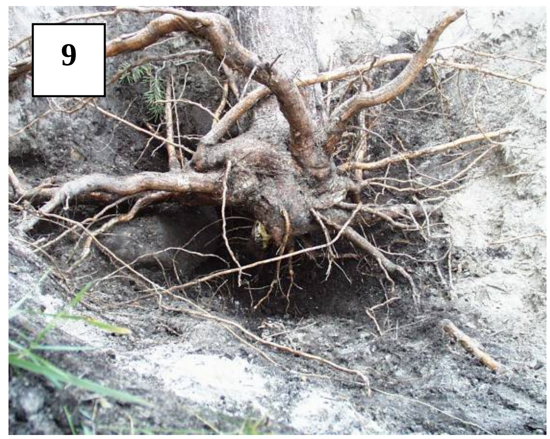
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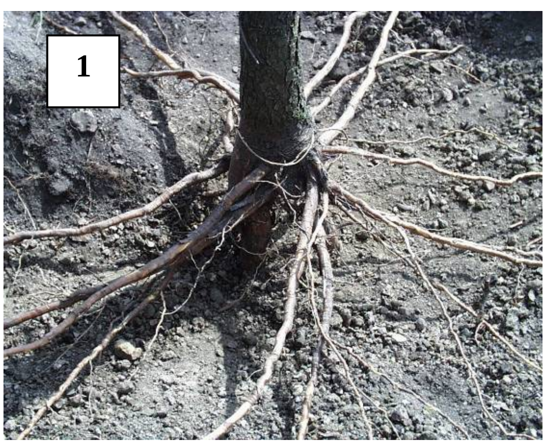
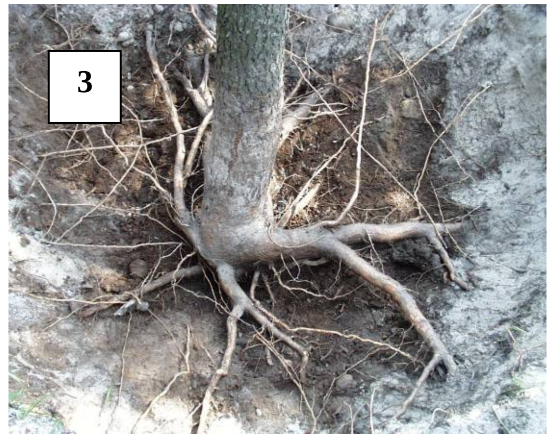
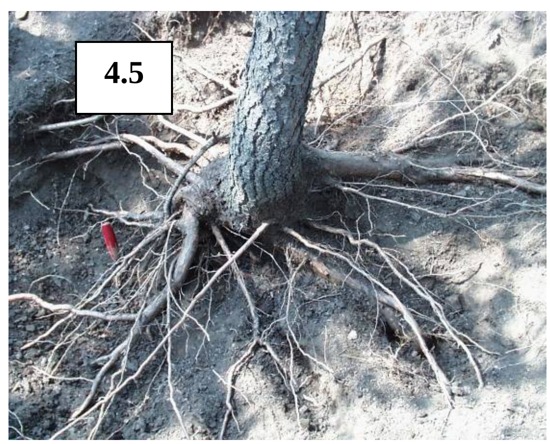
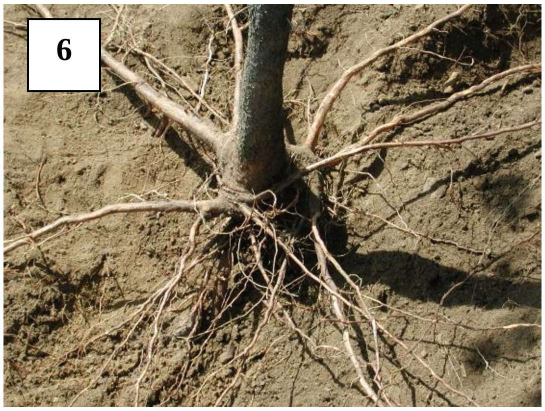
Coiling





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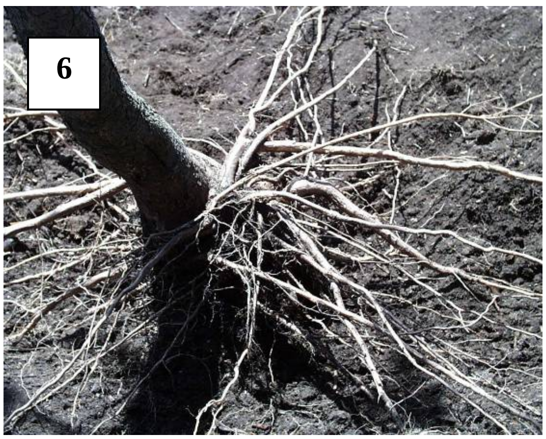
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